THE GEOLOGY OF ORE DEPOSITS

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AND

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ILLUSTRATED

EDITOR'S PREFACE

The economic aspect of geology is yearly receiving more attention in our great educational centres, and the books of this series are designed in the first place for students of economic geology. It is believed, however, that they will be found useful to the student of general geology, and also to miners, surveyors, and others who are concerned with the practical applications of the science.

'The Geology of Coal and Coal-Mining,' by Dr. Walcot Gibson, the first of this series of works on economic geology undertaken by experienced geologists, has already appeared. The present work will shortly be succeeded by others, dealing with the geology of quarrying, water-supply, and precious stones.

The Authors of this book have wide geological and mineralogical knowledge, a practical acquaintance with metalliferous areas, and an exceptional knowledge of the very extensive literature of the subject. This has enabled them to embody the important results obtained of recent years, which have added so largely to our understanding of the ways in which ores occur, and of the conditions under which they have been formed.

<div align="right">J. E. MARR.</div>

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AUTHORS' PREFACE

In this work our chief aim has been to present a concise account of the origin, mode of occurrence, and classification of metalliferous deposits. To keep the volume to a small and convenient size has been a task fraught with much difficulty, for hardly any subject has gathered round itself a greater mass of important literature than the Geology of Ore Deposits.

The choice of suitable illustrative examples, drawn from many countries, has been made with considerable care, and at the same time we have avoided in a great measure minor commercial details, which are often only of transitory interest. But while the geological features of the deposits form the main portion of the work, their close connection with the economic aspect of the subject has throughout been kept in view.

The size of this work, together with the vast and scattered literature with which we have had to deal, has rendered it impossible to make special reference to all the works and papers consulted, or to mention by name the numerous writers to whom we are indebted. We take this opportunity, however, of expressing our obligations to a great number of well-known authorities, and to the publications of several geological surveys and learned societies.

HERBERT H. THOMAS.
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GEOLOGY OF ORE DEPOSITS

CHAPTER I

INTRODUCTION

An ore deposit may be defined as a body of rock which contains metallic compounds or native metals in sufficient quantity and in such a form as to be of economic importance—that is to say, from which one or more metals can be profitably extracted.

The metals enter largely into the composition of the earth's crust, and it is conjectured on good grounds that, as a whole, they occur in increasing proportion towards the interior; for many of the richest ore deposits occur intimately connected with certain ancient igneous rocks and gneisses, on which the oldest recognizable sediments were deposited. Again, a great number of ore deposits have their origin in masses of igneous rock which have been injected into the solid crust from the molten interior of the earth; while others have been deposited from subterranean gases and solutions.

As a rule, it is the intrusive igneous rocks and the detrital or sedimentary rocks in their immediate neigh-

bourhood that are the richest in the compounds of the heavier and more valuable metals ; but taking into consideration the average composition of the earth's crust (see table below), it is clear that, in order to form an ore deposit, any particular metal or group of metals must have undergone considerable concentration. The following table compiled by Dr. F. W. Clarke gives an idea of the earth's average composition, as far as can be judged from surface observations :

	Per Cent.			Per Cent.
Oxygen ...	47·13	Carbon... ...	0·13
Silicon ...	27·89	Phosphorus ...	0·09
Aluminium ...	8·13	Manganese ...	0·07
Iron	4·71	Sulphur ...	0·06
Calcium ...	3·53	Barium ...	0·04
Magnesium ...	2·64	Chromium ..	0·01
Potassium ...	2·35	Nickel	0·01
Sodium ...	2·68	Strontium ...	0·01
Titanium ...	0·32	Chlorine ...	0·01
Hydrogen ...	0·17	Fluorine ...	0·01

The percentages of metals, other than those mentioned above, are too small to be given, only amounting to thousandths or millionths of 1 per cent. Certain fresh igneous rocks from mining districts in the United States, have been examined by Professor Kemp, who estimated that they contain the following metals in small quantities :

				Per Cent.
Copper ...	...	...		0·009
Lead ...	...	from	0·0011	to 0·008
Zinc... ...	...	from	0·0048	to 0·009
Silver ...	...	from	0·00007	to 0·00016
Gold... ...	...	from	0·00002	to 0·00004

The two tables given above make it quite obvious that every ore deposit must be due to some natural

process of concentration, by which the metalliferous material has been collected and deposited within a limited area; for no metal as originally distributed in any rock would exist in sufficient proportion to be of economic value. In this work we have endeavoured to explain the occurrence of ore deposits by presenting as concisely as possible the various processes Nature has adopted to bring about the local concentration of metalliferous material.

The original source of all ore deposits lay in the primitive igneous crust of the earth and in those igneous rocks which subsequently penetrated it from the interior. It may thus be said that the source of all ore deposits may ultimately be traced to rocks with igneous characteristics.

The igneous rocks which carry, or are answerable for, the richest metalliferous masses are mainly those of the larger intrusions. These are deep-seated or plutonic in character, by which is meant that they never reached the earth's surface in a fluid state, but were covered to a considerable depth at the time of their consolidation. Generally speaking, the older igneous intrusions—that is to say, those which belong to the pre-Cambrian and Palæozoic periods—are richer in ore deposits than those which have been intruded at a later date.

Deposits of considerable value are often associated with igneous rocks, occurring as dykes and small laccolites (hypabyssal), but are seldom found to be directly dependent on volcanic or extrusive rocks. This difference in the ore-bearing capacity of various igneous masses does not so much depend on any variation in the composition of the rocks themselves, as on the greater

facility which the plutonic rocks offer for the concentration of metalliferous compounds.

Ore-bearing igneous rocks, whether they belong to the most ancient fundamental complex of the earth's crust or were intruded into sedimentary rocks of later date, generally exist in the form of large masses, to which the name 'laccolites' is given, or as minor sheet-like intrusions with approximately parallel boundaries (sills and dykes). The ore deposits in the case of laccolites are often marginal—that is to say, they frequently mark the boundary between the igneous mass and the country rock into which it has been intruded; and the same is true in the case of those associated with the minor intrusions, but occasionally the ore may exist as rich strings or patches (*schlieren*) anywhere within the igneous rock, and not at its periphery.

The concentration of ore material and the formation of ore deposits in general has been brought about by a variety of processes, both physical and chemical.

In the case of those deposits formed by segregation from plutonic igneous rocks (p. 21), the concentration of ore has been determined by such factors as the crystallization of one mineral before another (fractional crystallization), or the separation of a homogeneous fluid into two immiscible fluids during the fall of the temperature towards the solidifying-point of the whole. Ore deposits formed in this manner are integral parts of the rock masses in which they occur. All igneous rocks in their most fluid condition are regarded as being homogeneous, and in that state are known as 'magmas.' The separation from a magma of any definite substance or of two immiscible magmas is looked upon as part of the process of segregation or differentiation described later

(p. 22). The separation of any mineral from a rock magma is analogous to the separation of a salt from its solution, and it is a well-known fact that many fluids which mix perfectly with each other at an elevated temperature, separate from each other, more or less completely, on cooling.

Metal-bearing gases and solutions may be given off from the larger igneous masses during their solidification. Metalliferous solutions may also be furnished by water charged with certain solvents passing upward or downward through rocks in which metallic ores are finely disseminated. These gases and solutions may subsequently deposit their metalliferous contents in fissures; or in the country rock with or without chemical interchange of material (pneumatolysis, hydatogenesis, and metasomasis).

All large sheets of standing water receive dilute metalliferous solutions from the surrounding dry land, and may either produce metasomatic changes in the rocks which form their beds, or may, on becoming saturated by evaporation or other causes, deposit their dissolved matter in the solid form (precipitations— p. 301). With such deposits are classed those which occur at the surface around springs, caused by the evaporation of the solvent or its removal by some other natural agency.

Since sedimentary rocks are detrital accumulations formed from pre-existing rock masses, it happens that finely divided stable metallic compounds or native metals present in the older rocks often undergo a concentration by natural agencies.

The above order of events—segregation from igneous rocks, pneumatolysis, hydatogenesis, precipitation, and sedimentation—seems to represent the most logical and scientific manner in which to group original ore deposits, on account of this being more or less the sequence taken by the various processes in Nature. Types of deposit formed in these various ways may undergo secondary changes, in the description of which in the following pages precedence has been given to metamorphosis produced by thermal and dynamic agencies.

Ore deposits generally may be roughly divided into two classes: first, those which have been formed contemporaneously with the enclosing rock (syngenetic); and, secondly, those which have formed subsequently (epigenetic).

The first class includes those deposits which form integral parts of igneous rocks, and many of those either chemically deposited from solutions or mechanically as detritus.

The second class embraces the greatest variety, and includes the ordinary veins and lodes, most metasomatic and pneumatolytic deposits, and all secondary enrichments.

The mode of occurrence of an ore mass is often dependent on the folds and fractures resulting from the movements which have taken place in the earth's crust. For in many cases these lines of weakness and dislocation are connected with the intrusion of igneous material, and also permit the easy access of mineralizing solutions or vapours to the country rock. On the other hand, movements of the earth's crust have often taken

place after the formation of ore deposits, so that these are then bent, broken, or in some other way altered in form.

The form of an ore deposit and the character of its outcrop will differ considerably according to whether the deposit belongs to the contemporaneous or subsequent classes mentioned above. A contemporaneous mass will of necessity take part in all the folding and faulting that the district may undergo ; and if in the form of a bed, its outcrop will be affected in a similar manner to those of the other strata with which it happens to be associated. Deposits of the second class will, as a rule, not conform to the outcrops of the rocks of the district, but will follow lines of disturbance, fracture, or some lines of weakness in the country rocks, with little or no reference to the original structure of the area.

Many of the richest mining districts occupy disturbed regions, such as mountain ranges, and the connection of the ore deposits with crustal movements may be regarded as quite intimate. In the formation of lodes and similar deposits, the sequence of events was generally an earth movement, either in the form of a crustal collapse or an upheaval, followed, or often accompanied, by volcanic activity or the intrusion of deep-seated igneous rocks. The sites of such disturbances were well suited for the formation of metalliferous deposits, owing to the facilities they afforded for the passage of mineral solutions and gases along fractures or crush zones, and also on account of the proximity of these disturbed areas to the igneous interior from which the metalliferous solutions were derived. When

such areas are intruded by igneous rocks, differing widely in composition, there may be corresponding different types of ore deposits formed. Some regions appear to have been disturbed several times, and on each occasion invaded by igneous intrusions, which successively gave rise to types of ore deposits, differing widely from one another.

The lodes in many metalliferous districts result from the infilling of fissures formed shortly after the intrusion and consolidation of the igneous rocks with which the ores are connected. The fissures, crush-zones and faults are in many regions parallel with one another, and have some definite directional character determined by the folding or cleavage of the rocks, and consequently with the direction of the earth-movements which developed these structures. Generally, however, such structures may be regarded as among the later effects of these general disturbances, and connected with the final movements of adjustment in the rocks.

In regions where the rocks have not been cleaved or highly folded, as is the case in many districts composed of the younger formations, the uniform directional character of lodes is not so noticeable. According to W. O. Crosby's theory of jointing, many lodes were formed by earthquake shocks, and, according to this writer, whatever other agencies, such as cooling or desiccation, might have operated within the rocks, the phenomena of parallel joints or veins is best explained by the assumption that they were created by earth-shocks, and that, if these take place slowly under bending or torsional strains, the direction of the fissures will be determined by the strain, while the 'time and mode of breaking' is determined by the shock. Extensive

fissuring and brecciation of rock due to earthquake shocks is found in many volcanic plugs. Such fissuring is therefore intimately connected with the disturbances produced during a period of volcanic activity.

It is probable that some fissures are formed by contraction due to cooling or desiccation of the rocks. Some igneous dykes are traversed by minute fissures formed during the cooling of the rock. The calcite-quartz veins in albite - diorite dykes in the Ready Bullion Mine, Alaska, appear to have been formed in this way. Some of the Cornish elvans (quartz-porphyry dykes) are traversed at right angles by innumerable small veins, varying in size from a thin film to a quarter of an inch or more. Occasionally tin ore is found along lines of parting, the direction of which was determined by the flow-structures, as in rhyolite in Cornwall. Fissures formed by contraction due to cooling also occur in quartz-porphyry in the Thüringerwald, where the veins contain manganese ores. In Victoria (Australia) gold veins are found in contraction-fissures in greenstone, and at the Haile Mine, South Carolina, in joints traversing diorite dykes. Although their origin has been disputed, the numerous veins traversing propylite at Nagyag in Hungary may be mentioned in this connection.

At Berezov, near Pyzhminskoye, in the Urals, greisenized granite veins, known as ' beresite,' varying from a few feet up to 150 feet in width, are traversed at right angles by numerous gold-quartz veins, giving a remarkable character to the auriferous mass.

The occurrence of argentiferous copper ore veins at Näsmark (Telemarken, Norway) traversing granite dykes at right angles has been noted by Vogt.

The remarkable occurrence of tin ore veins in pseudo-bedding planes in granite in the Erzgebirge has long been known. Here there are horizontal fissures parallel with the dome - like surface of the granite, and formed by contraction during cooling of the mass. More irregular contraction-fissures are found at Altenberg.

A particular form of fissuring connected with nickel-iferous deposits is formed by expansion of the parent rock during its serpentinization, but by far the greater number of lode-fissures were formed by external causes connected with movements of adjustment of the earth's crust, by which zones of shearing and faulting, as well as simple fracturing, are produced.

Where a district has been subjected to shearing, the metalliferous solutions may have deposited their material in a wide zone or belt of crushed rock. Such types of deposition are represented by some of the large cupriferous-sulphide ore bodies. Here, however, not only has there been deposition in the region of the crushing, but generally much of the material of the rock itself has been removed by solutions and replaced by new minerals. The structures of such lodes or ore bodies is consequently varied; but, although often containing very low-grade ore, the body as a whole, which is often lenticular in form, may be of great commercial value. Like the ordinary fissure lodes produced either by earthquake shocks or movements of adjustment at the close of regional disturbances, these impregnation-zones are also seen to be more or less parallel, the directional character being dependent partly on the direction of earth-stresses, and partly upon the structures of the rocks.

The original structures of the crush- or breccia-zones are preserved in the veinstones which are formed when the mass is mineralized.

The variety of structures which veinstones may present is infinite, and depends partly on the composition of the rock in which the lode has been formed, partly on the nature of the crushed or broken material which filled the fissures or lay between crush-planes before impregnation, and partly on intermittent deposition from the mineralizing solutions. In open fissures the comby, platy, or banded structures are seen to be due to the successive deposition of minerals arriving in the fissure at different periods. Where the original fracture contained brecciated material, the veinstones consist of strings and masses of ore penetrating and enveloping the fragmentary material, and so giving rise to exceedingly complex structures.

In rocks which can be decomposed and replaced by other substances, such as in the cases of the replacement-deposits of lead and fluorspar in limestone, and of tin and tourmaline in granite, the veinstones have a massive appearance, but frequently show dimly traces of the original structure of the rock.

In some deposits, as of smithsonite in limestone, a wonderful variety of concretionary structures are observed, apparently abstrusely connected with the change in volume which the rock suffered during its replacement.

It has often been remarked that lodes are seldom equally productive throughout, and that the ore occurs in patches, chutes, or bunches, as if the deposition of minerals had been favoured by certain places in the

lodes.   It is this local concentration of the ores that makes mining such a speculative enterprise, and renders prospecting and thorough sampling imperative.   The conditions favouring the local concentration of the original ores in lodes are many, and include primarily the proximity to the rocks from which the ores are derived.   The country rock has an influence where its composition is such that it can chemically react on the metalliferous solutions which penetrate it.   The texture of the rock and the degree of porosity are also powerful factors in modifying the nature and form of deposits.

In lodes originating under pneumatolytic conditions, the most favourable position for the principal ore bodies is near the margin of the plutonic igneous mass which gave rise to them, either in the external portion of the igneous rock itself or in its metamorphic aureole.   This applies also to pegmatitic deposits.   Of ores formed under pneumatolytic conditions, some are complex, and consist of oxidic and sulphidic compounds.   In this case, it not infrequently happens that the oxidic compounds are deposited in one zone or horizon in the lode, while the sulphidic compounds, owing probably to their more soluble nature, are deposited at a greater distance from the source.

In deposits of hydatogenetic and metasomatic origin, the solutions have often travelled considerable distances from the parent rock, and the metalliferous substances have been deposited in favourable places determined partly by mechanical conditions, and partly by the nature of the country rock.   In such cases, the form of the deposit is often influenced by the porosity and solubility of the rocks, which allows the solutions to seep through and impregnate the mass with ore.

It should be remarked that the solutions which percolate lode-fissures are either of magmatic origin (hydrothermal), being directly derived from some igneous rock, or of meteoric origin. In the latter case surface water percolating the lodes oxidizes and dissolves certain minerals near the surface, carries them down, and causes them to be deposited at lower horizons; while in the former case secondary actions are brought about by magmatic waters, as in instances where the nature of the solutions have changed and affected minerals deposited previously. That thermal waters derived from deep-seated sources contain much dissolved mineral matter of various kinds, capable of chemically acting upon the rocks they come in contact with, is proved by the nature of the dissolved compounds of thermal springs in well-known volcanic regions.

The alterations effected in this way have been classified into certain definite types, which may be referred to by such terms as silicification, propylitization, kaolinization, tourmalinization, axinitization, greisenization, scapolitization, sericitization, dolomitization, zeolitization, etc., according to the nature of the alteration effected by the solutions or vapours on the rock. Many of these alterations are complex, and others might be included in which thermal metamorphism has acted in conjunction with the solutions, with the production of such alteration types as garnet and epidote rock, or hornblende and pyroxene rock. It is unnecessary here to define all these terms, as they are self-explanatory, but it may be mentioned that some of them are particularly characteristic of the rock in the vicinity of certain kinds

of ores, and consequently also of the rocks from which the ores were derived. Practically all tin lodes, for instance, are characterized by a special kind of alteration of their walls, known as 'greisenization.' The felspar of granite is kaolinized by removal of the silicate of potash in solution. The same mineral is also converted into topaz, lepidolite, or gilbertite, through the reactions involved. Boron vapours have the effect of converting felspar to blue tourmaline, and biotite may be converted to brown tourmaline or to chlorite.

Where the lode traverses shale, the latter is often silicified or tourmalinized. Grits are converted to quartzitic rocks, and the tin ore is found interstitially or in minute cracks traversing the mass.

In calcareous rocks and greenstones the alterations effected by tin lodes consist of the development of axinite, fluorspar, garnet, and other minerals. Throughout the rock cassiterite or pyritic ores may be found among the alteration-minerals. All these actions are true metasomatic alterations, but, as in the majority of cases the principal part of the ore is found in or close to the original fissures, tin lodes are not regarded as deposits of metasomatic origin, since the metasomasis is only a subordinate phenomenon, and not the principal action, as it is in the case of many lead ore and fluorspar deposits traversing limestones.

A large number of ore deposits are in some manner chemically related to the rock in which they lie, whether they form integral parts of igneous masses or exist as deposits from vapours or solutions. This relation is most conspicuous in deposits which occur as parts of igneous masses, where similar metallic compounds are

almost always associated with certain rocks of definite chemical and mineralogical composition.

In the study of ore deposits, it has been found that many metals and compounds of metals which are chemically related are found in the same or similar deposits. Thus, for instance, platinum almost always occurs native associated with its allies, osmium and iridium. Cadmium occurs with zinc, chiefly in the form of sulphides, while the association of the allied metals iron, nickel, and cobalt as segregations is well known. Important exceptions may be noted, as, for instance, the case of the molybdenum, tungsten and chromium group. Here chromium is rarely found in any but the basic rocks, while tungsten and molybdenum are invariably found in association with the more acid rocks.

In the form of segregations, platinum and the allied metals osmium and iridium occur almost entirely in one type of igneous rock, and nickel and cobalt in another; while among metasomatic deposits zinc and cadmium are most often found in association with limestones. Tin ore lodes are always associated with granite or its fine-grained modifications, the quartz porphyries, and, in the case of certain definite types of ores, the geological conditions, with slight modifications, are repeated the world over. Most ores have as almost constant associates other less valuable metallic compounds, or some non-metallic minerals, which are most helpful in throwing additional light on the modes of formation of the ore deposit as a whole, and which are occasionally of great assistance to the prospector. The occurrence of chromite with platinum; fluorspar and barytes with galena and zincblende; cinnabar

with gold; tourmaline, topaz and lithia-mica, with wolfram and tin ore, are only a few instances.

From a study of many examples, it has been found that the minerals forming ore deposits have a more or less regular order of deposition, the formation of certain minerals regularly preceding or following others with which they are associated.

This is especially true in the case of segregations from igneous rocks, in which the formation of metallic sulphides and oxides generally precedes that of the silicates which form the bulk of the rocks.

Again, where similar compounds of two metals are segregated in one deposit, one will precede the other, as, for instance, the case of the sulphides of nickel, which are formed before those of cobalt.

Where an originally barren rock has been replaced by an ore deposit, it is again noticeable that the metallic minerals have a definite sequence. In ores formed under pneumatolytic or hydatogenetic conditions, the sequence of mineralization is generally readily made out. The order in which the minerals were deposited in the Cornish tin-copper lodes has been referred to in the following pages, and serves to illustrate this point.

Amongst the metallic minerals forming ore deposits, and which occur as segregations from igneous rocks, are the native metals, such as platinum; the oxides of iron with and without titanium, and the sulphides of iron, nickel, cobalt, and copper.

The replacements include chiefly the sulphides of iron, lead and zinc; the carbonates of the same metals,

with manganese in addition; the oxides of iron and manganese, and, less frequently, native gold.

The metamorphic deposits are especially noted for their masses of magnetite and iron and copper pyrites.

Precipitations consist chiefly of oxides and carbonates, as might be expected from their mode of deposition.

Bedded detrital deposits may contain gold, platinum, tinstone, iron ores, etc.—in fact, any metal or compound of a metal which is sufficiently durable and insoluble to withstand the long-continued action of meteoric agents.

The changes which ore deposits may undergo after their original formation may be divided into three classes : dynamic, thermal, and chemical.

The dynamic changes, often included under the head of 'metamorphosis,' consist chiefly in the deformation of pre-existing deposits, their disruption, brecciation, and displacement, and the setting up of certain structures due to shearing stresses in the earth's crust.

The thermal changes produced by the heat of the earth's interior or the intrusion of igneous rocks include chiefly the production of new minerals or the recrystallization of those which already existed, but, like the changes connected with dynamic agencies, are independent of the introduction of any new material from outside the affected area.

Among the secondary changes of ores brought about by chemical actions, the most important is that effected by the oxidizing and dissolving action of surface waters which find their way into lodes and other kinds of metallic deposits. By these waters (' meteoric waters ')

not only are certain minerals completely decomposed and fresh minerals formed, but a secondary concentration of the ores is effected by the reduction of metalliferous substances brought down in solution to depths in the lode beyond the reach of oxidizing influences.

In this way secondary enrichments are formed, which in some districts are the only parts of the deposits worth working. The metalliferous minerals which are uninfluenced by the surface waters comprise tinstone, wolfram, scheelite, and a few other compounds. Others are not affected unless the water already contains some salt in solution, as, for instance, in the case of the solution of metallic gold by ferric sulphate and its reprecipitation by ferrous sulphate. As a whole, then, the chemical changes brought about in lodes by the action of meteoric waters may be broadly described as those of oxidation and solution near the surface, followed by reduction at a variable depth in the lode, depending upon the distribution of ground water, which in turn is largely dependent on the climate and structure of the country. The minerals most liable to these secondary chemical changes are the sulphides, and the iron and manganese ores. The secondary minerals formed in this way comprise sulphides, sulphates, silicates, carbonates, and oxides. But some phosphates, vanadates, arsenates, and other compounds, are also formed, together with native metals, such as copper, silver, and gold. The distribution of ground water has been dealt with in the following pages, but it should here be remarked that we do not accept in its entirety the hypothesis that most ores are concentrated by the action of circulating waters. According to some writers, the meteoric waters are supposed to percolate through the rocks from

the surface, and to descend to great depths, collecting metalliferous minerals as they go. With increasing depth their powers of solution are augmented by pressure and heat, and on reascending, the metalliferous minerals are redeposited in fissures. In the newer and porous rocks a redistribution of certain minerals by such means does not appear improbable, but in the case of the Palæozoic and Archæan rocks it appears more likely that the meteoric waters have played only a subordinate part in the formation of ore deposits, and in all cases the re-concentration of the ores by chemical actions is confined to shallow depths.

The various classes of ore deposits as set out in this work embrace most of the better-known occurrences. At the same time it must be borne in mind that any classification of this kind can only be arbitrary, and that there are many instances of an ore deposit being equally well assignable to two positions in the scheme of classification. This, it is true, often arises from the meagreness of the information obtainable, but in other cases there is a distinct overlapping of two classes, and thus it becomes a matter of some difficulty to decide the proper place that certain ore deposits should occupy.

It often happens, for instance, that a deposit may be classed equally well with the metasomatic or metamorphic deposits. Many of the lodes formed under pneumatolytic conditions are characterized by metasomatic alterations in their walls ; but as this is only an attendant phenomenon, and not the principal point of interest in connection with the origin and nature of the deposit, this peculiarity is subordinated in the scheme of classi-

fication to certain types of ores. As in other cases, the form of the ore body was determined solely by the extent of the metasomatic replacement. A special group of deposits is treated under the separate heading of Metasomatism.

It has been the endeavour of the writers to present the main geological features of metalliferous regions as far as they bear on the origin and nature of the particular deposits described, and to classify them according to the leading types. For more detailed accounts of their commercial value the reader is referred to standard textbooks, and in particular to ' A Treatise on Ore Deposits,' by Phillips and Louis; ' Die Erzlagerstätten,' by Stelzner and Bergeat; ' Gîtes Métallifères,' by Fuchs and De Launay; ' The Nature of Ore Deposits,' by Beck (translated by Weed) ; ' The Copper Deposits of the World,' by Weed; and ' Ore Deposits of the United States,' by Kemp. Other important sources of information are the ' Memoirs of the Geological Survey of the United States of America,' the ' Zeitschrift für Praktische Geologie,' the ' Transactions of the Institute of Mining and Metallurgy,' and the ' Transactions of the American Institute of Mining Engineers.'

CHAPTER II

ORES DUE TO THE DIFFERENTIATION OF IGNEOUS MAGMAS

A CONSIDERABLE number of ore deposits are intimately associated with masses of igneous rock, in such a manner as to prove without possibility of doubt that they have been derived from, and formed part of, an igneous magma. These deposits must be regarded as part of the igneous rock with which they are associated, for they stand petrographically related to the rock-masses, and there is no evidence of the introduction of material from outside sources by solutions or pneumatolytic processes (p. 72).

It has been clearly demonstrated that many igneous masses are far from homogeneous in character, and that the chemical composition varies considerably from one part of the mass to another. This lack of uniformity, which is regarded as the result of a process or series of processes, to which the name 'magmatic differentiation' has been applied, often takes place gradually, and is chiefly noticeable in the falling off of the amount of silica in the rock towards its margin. In many cases it is safe to assume that a magma, prior to its intrusion into the upper regions of the earth's crust, was practically homogeneous, but that, as soon as it commenced to cool, certain differential processes started to operate

within the fluid, resulting in a local concentration of certain mineral constituents.

A study of any rock-mass of igneous origin, either extrusive or intrusive in character, reveals the fact that the various minerals of which it is composed separated out from the mother-liquid at different times, and generally in a more or less definite sequence.

The earliest substances to separate out from a cooling igneous magma are, generally speaking, the native metals, the metallic oxides, and the metallic sulphides; these are usually termed 'accessory minerals,' owing to the fact that they form, in most cases, an insignificant part of the rock-mass as a whole. These are followed closely by those silicates rich in iron and magnesia, such as olivine, the pyroxenes and amphiboles, leaving the last portion to consolidate richest in silica and poorest in the heavier basic constituents. Normally the accessory minerals should be distributed sparingly, and more or less uniformly, through the rock-mass; but we observe that they have often undergone considerable concentration, in many cases occurring in sufficient quantity to constitute an ore.

The processes which brought about the concentration of the accessory minerals are exceedingly complex, but they were certainly initiated by various portions of the fluid magma being at different temperatures owing to the cooling of the mass.

Differentiation is the outcome of either a fractional crystallization of the various constituents of an igneous magma, or a separation of a magma into two or more solutions which will not mix; from which it follows that the concentration of a mineral depends primarily

on the temperature at which it crystallizes from, or becomes insoluble in, the mother-liquor, governed at the same time by such factors as the rate of cooling of the magma as a whole, and on the degree of its viscosity during the process of differentiation. It is a noteworthy fact, evidently connected with the process of differentiation, that in any magma the concentration of a series of minerals takes place in the same order as that in which they crystallize ; and the greater the difference between the solidifying temperature of a mineral undergoing concentration and that of the next mineral to crystallize after it, the more slow the cooling, and the greater the mobility of the magma promoting free convection and diffusion, the more complete will be the concentration of the mineral in the cooler zone.

It has been proved that the viscosity of different igneous magmas and of artificial slags near the temperature at which they commence to crystallize varies considerably, according to the chemical composition ; and that, as a general rule, the more basic magmas, those with the lower silica percentage and in which soda-lime and ferromagnesian minerals play an important part, are the more mobile.

It is not surprising, therefore, to find that in the basic and ultrabasic magmas, especially those which have consolidated at great depths below the earth's surface, the migration of the accessory constituents to the margin of the mass has been most pronounced.

Magmas such as those of peridotites, picrites, and allied olivine-bearing rocks, as well as those of a great number of rocks with gabbro affinities, such as the norites, pyroxenites, essexites, kersantites, etc., may on differentiation yield varying quantities of platinum,

gold, osmium, iridium, nickel, cobalt, iron, titanium, copper, etc., occurring in the form of native metals, oxides, or sulphides, as the case may be.

To illustrate the result of the processes of differentiation in a basic igneous rock-magma, we cannot do better than take such a well-known English example as that of the gabbro of Carrock Fell in Cumberland, described by Mr. Harker.

A large mass of gabbro was intruded into Lower Palæozoic sediments; the intrusion has a more or less symmetrical outline, and covers an area of about six square miles. There can be little doubt that the gabbro was intruded as a homogeneous mass, but that, as it came to rest and began to cool, differentiation commenced with crystallization and concentration of the more basic minerals towards the margin, leaving the silicious material more prevalent towards the centre.

The accompanying map, based on the work of Mr. Harker, shows most clearly how various portions of the mass differ in chemical composition.

The margin of the gabbro consists of a rock very rich in ilmenite, and also richer in pyroxene than that towards the centre; it has a silica percentage of only 32·5, and the iron ores, ilmenite and magnetite constitute 21 per cent. of the total rock.

The centre of the mass, however, is a quartz-bearing gabbro, with a very small quantity of iron ores, not more than 1 per cent., and the relatively high silica percentage of 53·5.

These two extreme types pass through an intermediate variety, which may be styled a normal gabbro neither rich in iron ores nor containing free silica in the form of quartz.

The above is a most simple example of the differentiation of a rock-mass in place, by which it is meant that the differentiation took place in the area where its results can now be studied. In a great number of cases,

QuartzGabbro

NormalGabbro

Ilmenite Gabbro

Granophyre

SkiddawSlates etc.
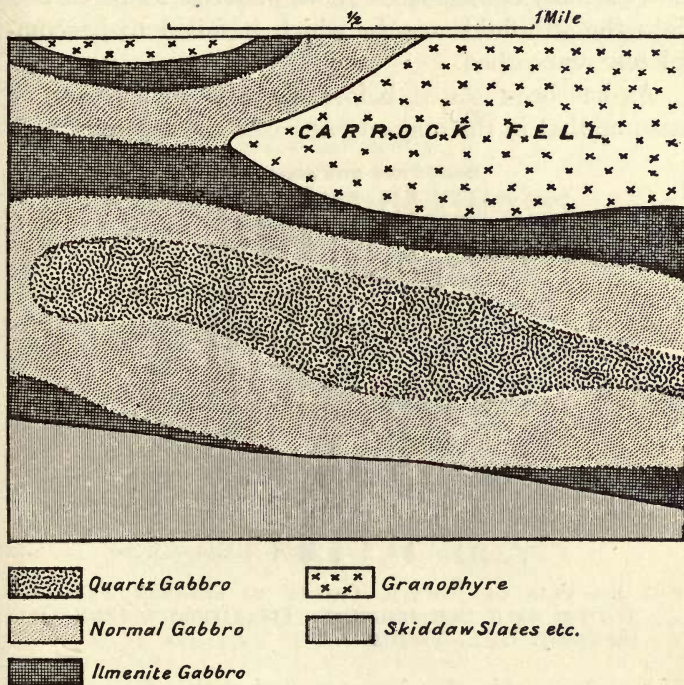
FIG. 1.—MAP OF THE CARROCK FELL DISTRICT, CUMBERLAND, TO ILLUSTRATE THE DIFFERENTIATION OF A GABBRO-MASS AFTER INTRUSION. (AFTER A. HARKER.)

however, it is found that the products of differentiation are not so symmetrically arranged as in the above case, but the more basic ore-bearing material occurs as patches or strings (schlieren) in a less basic part of the rock.

It is supposed that these basic patches and schlieren owe their origin to either convection currents or shearing stresses acting on the magma during the process of consolidation, causing portions of the already segregated and partially consolidated basic material to be carried into the still-fluid mass by which it failed to be completely reabsorbed.

As has been stated before, there is good reason to assume that in the majority of cases the differentiation

IGNEOUS VEIN WITH SCHLIEREN

FIG. 2. — VEIN OF NORITE, THIRTY TO SEVENTY YARDS IN WIDTH, WITH SCHLIEREN OF TITANIFEROUS IRON ORE. (AFTER J. H. L. VOGT.)

of a rock-mass is closely connected with, and probably dependent on, the crystallization of its constituent minerals; but certain banded ores, which, on account of the extreme type of differentiation they exhibit, present marked affinities to the gneisses, seem to have had a different genesis.

The ores—*e.g.*, ilmenite, magnetite, etc.—in rocks of this type occur generally as narrow ultrabasic streaks

separated by less basic material. It is, moreover, evident that these ore-bearing layers and the less basic material between them crystallized simultaneously, and that they existed together in the fluid state.

It is probable that the various layers are the result of the intrusion of a magma which had differentiated,
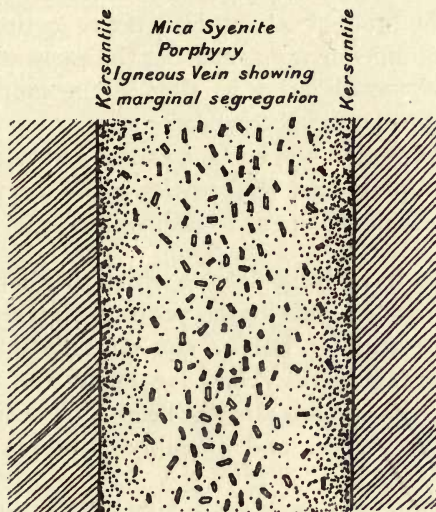
FIG. 3.—VEIN OF MICA SYENITE-PORPHYRY, SHOWING MARGINAL SEGREGATION OF FERROMAGNESIAN MINERALS AND IRON ORES. (AFTER J. H. L. VOGT.)

before intrusion, into two or more magmas which did not intermingle. That is to say, that the original magma was in this case heterogeneous at the time of its intrusion, and that the differentiation was in a great measure independent of the crystallization of the individual minerals.

With regard to the differentiation of sills and dykes,

or the lesser intrusive bodies generally, the segregated minerals are identical with those from similar magmas existing in the larger masses, but the differentiation is not often so well displayed.

It has been noticed that occasionally sills and dykes show a concentration of basic minerals on their lower surfaces, and it is here supposed that the differentiation was largely brought about by gravity acting on the partially solidified magma, causing the early and heavier products of consolidation to sink in the mother-liquor and to form a basic substratum.

Rocks erupted at the surface as lavas have in general cooled so rapidly that differentiation on anything like a complete scale was next to impossible.

So far we have been dealing chiefly with the differentiation of a magma in the position in which we are now able to study it, but we can conceive many rock-masses existing in reservoirs far below the surface of the earth, which have already been differentiated into various rock types, and possibly with ore deposits marking a zone.

Such a differentiated mass under the influence of increased temperature and earth movement might be intruded into higher and cooler regions of the earth's crust.

The intrusion of this rock-mass would take place in successive stages, and each stage would be characterized by a magma of different chemical composition.

From these magmas would originate a group of rocks differing widely from each other in type, but yet tied together by some common mineralogical characteristic, such as the presence of hypersthene, for instance

Fundamental Gneiss & Schist.
Devonian & Silurian Slate Sandstone & Conglomerate.
Gabbro-Diabase.
Laurvikite.
Mica-syenite.
Laurdalite.
Akerite.
Nordmarkite.
Soda-Granite.
Granitite.
Rhombporphyry & Augite-Porphyrite.

POST-SILURIAN IGNEOUS ROCKS INTRUDED IN ORDER OF DECREASING BASICITY.

URDFASEN
NORDMARKEN
FINNMARKEN
KRISTIANIA
DRAMMEN
KONGSBERG
DROBAK
HOLMESTRAND
MOSS
HORTEN
FREDRIKSTAD
SKIEN
TÖNSBERG
BREVIK
LAURVIK
SANDEFJORD
KRAGERÖ
BAMLE
LANGESUND

0 4 8 12 16   32 Miles
SCALE

Fig. 4. — General Geological Map of the Christiania
Region, showing the Distribution of Various Rock
Types derived from a Magma differentiated before
Intrusion. (After W. C. Brögger.)

(p. 41).   The rock-masses thus formed, although they occur in one district, and are possibly in contact with each other, will not graduate one into the other, but will be separated by hard - and - fast lines.   Taken together they will form what is known as a ' petrological complex,' or a group of cognate igneous rocks.

A study of such a group of rocks will show that they were intruded in a more or less definite order, and that this order was usually one of basic to acid in the case of the larger plutonic masses, and acid to basic in the later minor intrusions.

These rock-masses, although they are themselves products of differentiation before intrusion into their present position, have in most cases undergone further differentiation in place, and have often given rise to a series of satellitic dyke rocks.

In the more basic rocks which have thus undergone a double process of differentiation, marginal concentration of ore material is often exceedingly well displayed. Examples of such cognate groups of igneous rocks are extremely numerous, but perhaps the best known are those of Essex County, Mass., and of the Christiania district of Norway, where the rocks vary from an olivine-gabbro-diabase, with a silica percentage of 46·5, to a potash granite with 64·2 per cent. of silica.

Pegmatites, which are often the carriers of many rare minerals, are highly silicious igneous rocks, generally the direct result of the differentiation of the less basic plutonic magmas, and represent the most acid and unconsolidated part of a differentiated mass squeezed out into the surrounding rocks.   In a petrographical complex they are usually seen to be the latest products of consolidation,

and to cut all the other igneous rocks of the series to which they belong. They are especially interesting on account of the minerals occasionally met with in them, amongst which are several containing the rarer elements, cerium, lanthanum, didymium, yttrium, thorium, etc. It has been suggested that certain gold-bearing quartz rocks are the ultimate products of the differentiation of an igneous magma, and that they represent one phase of differentiation beyond that presented by pegmatites, aplites, and allied rocks (p. 33). A hydrothermal phase of some pegmatites is now recognized, and is generally represented by silicious deposits (often containing rare minerals) formed in fissures as a continuation or prolongation of the pegmatite. This ultimate phase is explained by the fact that the pegmatites with which it is found contained a considerable amount of water, which was given off as solutions rich in silica and other substances during the final stage of consolidation of the pegmatite.

The researches of Vogt in Sweden and elsewhere, and his deductions, form the natural basis for any classification of segregated ore deposits. In following him, we shall divide the ore deposits which are the results of magmatic differentiation into three groups, as follows :

1. Segregations of native metals.
2. Segregations of metallic oxides.
3. Segregations of metallic sulphides.

It must be understood at the outset that all these groups merge into each another, and necessarily overlap ; for it is just as difficult to draw a hard-and-fast line between the various types of ore deposits as it is to

trace the shades of difference in the various rock-masses to which they owe their origin.

SEGREGATION OF NATIVE METALS.

There are many well-authenticated examples of native metals occurring in association with igneous rocks in a manner which proves their igneous origin, but very little is known concerning their segregation, or of the state in which they were carried by the igneous magma. So far the chief metals known to occur native in igneous rocks are gold, platinum with osmium and iridium, nickel, and iron, and these all seem to be present as original constituents. In some few cases it can be proved that they have undergone a certain amount of concentration during the solidification of the respective magmas by which they are carried.

Gold.—That gold is an extensively distributed constituent of igneous rocks is proved over and over again by its widespread occurrence in alluvium of all ages formed from the waste of igneous rocks under the influence of denuding agencies. But apart from this indirect proof, free gold has been detected in a great variety of rock types, amongst which may be mentioned granites, pegmatites, diabase, diorite, and others of still more basic character.

From a choice of many examples, it may be stated that free gold occurs in the granites of Brazil and of Sonora in Mexico. The pegmatites and allied rocks have yielded this metal in the Dargo and Omeo districts of Victoria, Australia, in the Berezov district of the Ural Mountains, in the Silver Peak district of Nevada, and the Yukon district of Alaska. The diabases and diorites of British Guiana, the Appalachian

region, Queensland, and many other districts, have been proved to be parent rocks of much gold now occurring in placers (p. 381). Gold has been noted as an original constituent of porphyritic syenites in British Columbia and other adjacent areas; in pitchstone in Chili; and in peridotite from Damaraland. In the Australian plutonic rocks it has only been found in association with pyrites. With regard to the occurrence of gold in Nevada mentioned above, a word or two will not be out of place concerning its mode of origin.

It is contained in quartz-felspar rocks, to which the name *alaskite* has been given; this rock graduates into pure quartz, which is looked upon as the ultimate product of differentiation of a granitic magma. The Silver Peak district is one of abundant granitic rocks, which are intrusive into the Palæozoic strata. These muscovite-biotite granites pass into aplitic and pegmatitic types consisting of quartz and alkali-felspar. The alaskite, by the diminution of felspar, passes into pure quartz veins, which are said to have the same genetic relation to the alaskite as it has to the granite.

These quartz veins, often of lenticular form, are the source of much gold, and a figure showing their mode of occurrence is given below.

By far the greater number of rich alluvial gold deposits have been derived from igneous rocks of an intermediate to basic character, and it can be proved that the gold in the placers of certain districts like British Guiana is dependent on the distribution of diabase and diorite. In other cases of more rare occurrence, alluvial gold has been derived from rocks of granitic character, including pegmatites and aplites. An example may be

cited from the Blagovyeschensk district, on the borders of Siberia and Mongolia.

Free gold is found associated with platinum in the chromite segregations from basic and ultrabasic rocks, such as peridotite and other olivine-rich igneous masses (p. 53). The gold placers of the Goroblagodat region in the Urals and of South-West Oregon have had their origin in rocks of this nature.
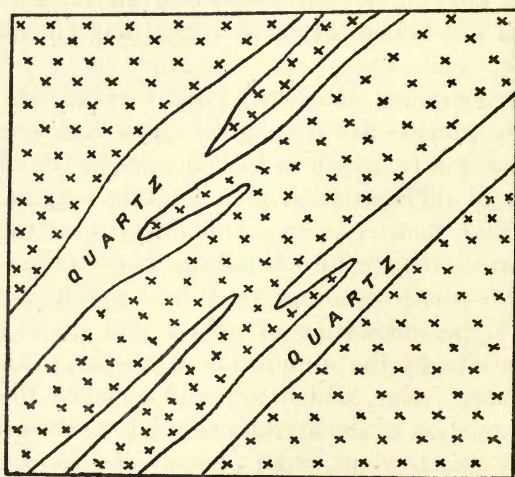
FIG. 5.—SECTION TO ILLUSTRATE THE MODE OF OCCURRENCE OF AURIFEROUS QUARTZ LENSES IN ALASKITE.

Platinum.—As far as our knowledge goes, native platinum, as an original rock-constituent, is restricted to the most basic igneous rocks, such as peridotites and their altered equivalents, serpentines. With platinum are associated the two allied metals osmium and iridium, which are usually combined with each other to form the alloys osmiridium and iridosmium. Platinum,

with the metals mentioned above and some gold, is extracted from the more basic parts of peridotite, dunite, and serpentine masses occurring in the Ural Mountains at Nizhne Tagilsk, Mount Solovief, and other districts, and placers have been worked in the valleys of the rivers Issa, Wyja, Tura, and Njassma, which drain the peridotite and serpentine region.

Similar placers derived from similar rocks have been worked in Northern California. The dunite of the Tulameen River, British Columbia, contains platinum associated with chromite. A single but unconfirmed record of platinum from the Lizard Peninsula in Cornwall is interesting on account of the parent rock being of the usual type which bears this metal.

Platinum is almost always associated with segregations of chromite (p. 53), and, though all chromite segregations do not carry platinum, this mineral is an important indicator of the rarer metals ; therefore the necessity of examining all alluvial deposits draining a region of basic igneous rocks with chromite segregations cannot be too strongly urged.

Iron. — The most striking occurrence of a native metal of true igneous origin is that of the iron masses of Disco Island, on the west coast of Greenland. Large blocks of almost pure iron were first detected lying loose on the hill-sides at Ovifak, and were originally supposed to have a meteoric origin, their resemblance to meteoric masses being most marked both in appearance and composition.

Subsequently this iron-bearing rock was discovered in place, and was found to exist as extremely basic patches occurring in, and differentiated from, a basalt porphyrite.

The porphyrite consists of labradorite, augite, olivine, and titaniferous magnetite, set in a glassy ground-mass, while the basic patches consist chiefly of anorthite and native iron in grains and lumps. The ore has the following composition :

					Per Cent.
Fe ...	...	...	...	...	92·91
Ni ...	...	...	...	...	2·66
Co ...	...	...	...	...	0·69

A curious feature is the relatively high percentage of carbon, 3·29, which probably exists in the form of graphite.

It has been suggested that the porphyrite was volcanic or extrusive in character, but such an origin cannot be assigned to it without further evidence, especially as the character of the rock and the extreme differentiation which has taken place point in the direction of intrusion.

The nickel in the above ore probably exists as an alloy with a small proportion of iron, similar to that described below.

Many eruptive rocks, and particularly the basalts (*e.g.*, Ireland, Spain, America, Germany), contain minute grains of native iron, in some cases enclosed by magnetite.

Nickel. — An alloy of nickel with iron, in which nickel preponderates, seems to be a product of the differentiation of certain peridotites and olivine gabbros. The more usual alloy is that to which the name 'awaruite' has been given, after the district Awarua in New Zealand. In chemical composition it compares very closely with some nickel-irons occurring as meteorites, and contains 67·63 per cent. of nickel, 0·70

per cent. of cobalt, and 31·02 per cent. of iron, corresponding to the formula, 2Ni + Fe.

In New Zealand, on the west coast of the South Island, large masses of peridotites have been intruded into the crystalline schists of that region, forming the Hope, Olivine, and Redhill Ranges. They are somewhat variable in character and partially serpentinized, but usually contain enstatite. They occupy an area of 400 square miles, the greatest length being twenty-five miles. Awaruite is the chief product of differentiation, but with it are segregated small quantities of the usual accessory minerals of peridotites, chrome-iron ore (chromite) and chrome-spinel (picotite). This alloy was first recognized in the alluvial deposits of the River George, which drains the peridotite-country of the Olivine Range.

Amongst other localities, nickel alloyed with some iron is present in the alluvium of the River Elvo, in Piedmont, Italy, where it has probably been derived from the nickel-bearing serpentines of the Southern Alps; it also presumably occurs in this state in the Disco iron-masses (p. 35).

SEGREGATION OF METALLIC OXIDES.

Oxidic segregation, or the local concentration of metallic oxides in igneous rocks, is one of the most marked phenomena connected with some types of igneous intrusions.

To this class of ore deposits belong the segregations of the titaniferous iron ores—existing as titaniferous magnetite and ilmenite—chromite, corundum, and possibly some cassiterite (tinstone). All these segregations, with the exception of cassiterite, are from basic igneous

magmas, and exist either as ultrabasic dykes and masses due to differentiation of the magma before intrusion, or as ultrabasic margins to plutonic masses and dykes of basic character differentiated in place.

In the case of the titaniferous iron ores, most of the ore deposits form sharply defined masses which do not graduate into the country rock, and were evidently intruded as dykes or small bosses subsequently to the intrusion of the more acid members of the series to which they belong and within which they occur.

Dykes in which marginal concentration of metallic oxides has taken place are not uncommon, and oxidic segregations also occur in the parent rock as basic patches, strings, and schlieren. The chief rock-types yielding these ore deposits belong to the great gabbro and peridotite groups, and include such rocks as gabbros with and without olivine, ophitic dolerites with and without olivine, norites, nephelinites, peridotites, and picrites.

It is particularly noteworthy that within certain limits the rocks which yield a segregation of one oxide differ in character and composition from those segregating a different oxide; thus, for instance, we find titaniferous magnetite segregated by the olivine-gabbro of Taberg (p. 42), ilmenite by the hypersthene-gabbro and norites of the Ekersund (p. 41), and chromite and corundum by peridotites.

Together with these concentrations of oxides, as has been pointed out before, there has been a segregation of the bisilicates, such as olivine, hypersthene, etc., and often of phosphorus in the form of apatite (chlorapatite), so that it is seldom found possible to obtain the ore unmixed with other minerals.

SEGREGATION OF IRON ORES AS OXIDES.

Oxides of iron, usually with a large percentage of titanium oxide, are fairly common products of differentiation of many gabbro and norite magmas, and they occasionally occur associated with less basic rocks of the porphyry and nepheline syenite types, the latter containing generally less titanium oxide and more apatite. In the more basic rocks, with a silica percentage of less than 55, owing to the simultaneous segregation of the ferromagnesian silicates, the ores exist as an intimate mixture of titaniferous magnetite, or ilmenite, with some mineral such as olivine or hypersthene, and may be referred to under such names as ilmenite-enstatite rocks or magnetite-olivine rocks, according to the two dominant constituent minerals.

Often with the iron ores are segregated small quantities of chromite, and they may contain manganese; but maganese, compared with iron, undergoes very feeble concentration. The percentage of phosphoric acid varies remarkably in the various rocks differentiated from the same magma; in the earliest intrusion it is often exceedingly small, but rises gradually to about 2 per cent. in those which follow. Generally speaking, however, the titaniferous iron ores are characterized by a relatively low percentage of phosphoric acid. The part played by titanium in these ores has been ably studied by Vogt, who suggests that titanium takes the place of silicon, and that, in titaniferous magnetite and ilmenite, titanium oxide acts as an acid radicle, and combines with the iron oxide to form ortho- and metatitanates having the general formulæ R_2TiO_4 and $RTiO_3$, where R stands for iron, possibly replaced in part by

small quantities of magnesium and manganese. The orthotitanate is generally titaniferous magnetite segregated by the olivine-gabbro magmas, while the metatitanate is ilmenite associated with the hypersthene-bearing rocks.

The ilmenite segregations may be said to bridge the gap between segregations of orthotitanates and segregations of metallic sulphides, for in most of them we meet with a fair percentage of sulphides. With the segregations of orthotitanates we most often get concentration of the metasilicate, an example of such a combination being displayed by the magnetite-olivinite of Taberg; while metatitanates occur with orthosilicates in the ilmenite-hypersthene rocks of the Eker-sund-Soggendal district.

True magnetite deposits are seldom if ever met with as segregations from igneous rocks. The ore-masses given rise to by the more acid magmas, such as those of the nepheline syenites (p. 52), approximate more nearly to pure magnetites than any of the ones from the basic igneous masses. At the same time, however, the percentage of phosphoric acid is liable to increase. Magnetite ores, without titanium and with a low percentage of phosphorus, are almost always associated with the crystalline schists and other metamorphic rocks; and it is more or less evident that they have been formed by the metamorphism of pre-existing iron deposits of sedimentary or metasomatic origin (pp. 336, 339).

Iron Ores from Gabbros and Norites.—In Southern Norway and Sweden occur numerous masses of igneous rocks belonging to the gabbro family, and from these have been segregated some of the most famous iron ores

of the world. They were studied by Vogt and others, and, as regards the origin of the ores, are probably better understood, and have received more attention of a scientific nature, than masses of similar rocks in any other country. The district of Ekersund-Soggendal, in Southern Norway, forms a well-defined petrographical province, of which the various rock-members are especially characterized by the occurrence of rhombic pyroxenes (hypersthene, etc.), and were evidently derived from a common magma-basin.

This district furnishes us with a most typical example of the segregation of ilmenite from magmas of a noritic character, differentiated before their intrusion into their present position. The rock-types occurring in this province range from a hypersthene-bearing rock, rich in labradorite, through ilmenite-norite, which occurs as dyke-like masses in the labradorite rock, into an almost pure ilmenite rock containing varying amounts of hypersthene, and perhaps a little felspar. The pure ilmenite deposits, when in the form of dykes, cut the ore-bearing norites, and are therefore the last to be intruded. The labradorite rock compares very closely with the *anorthosite* of South-East Canada and the Adirondack district (p. 45), where the iron ores have a similar origin.

The iron ores of the Ekersund-Soggendal occur partly as segregations from the norite dykes, where they exist as ilmenite-norites, and partly as veins, schlieren, or basic patches, which occur in the labradorite rock, having well-defined boundaries.

The ore in the norite dykes, such, for instance, as that at Storgangen, where the ' big ore ' occurs, consists of an intimate mixture of ilmenite and hypersthene, with

a little labradorite, and makes up 40 per cent. of the total rock.

In the basic strings and patches, such as at Blaafjeld, ilmenite predominates to such an extent that the rock loses its norite character, and the percentage of iron ore rises to 90 or 95. The Blaafjeld masses, however, are exceptionally pure, the more usual percentage for the purer ores being 70 to 80.

The magnetic iron ore deposits of Taberg in Smaland, Sweden, consist of titaniferous magnetite, and differ chiefly from ores of the Ekersund-Soggendal type in this respect, and in the fact that the parent rock is
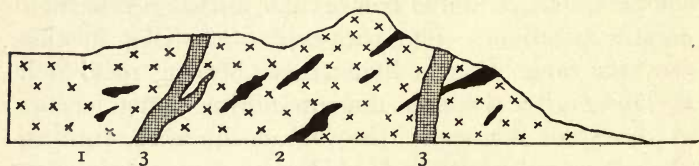
FIG. 6.—SECTION TO ILLUSTRATE THE MODE OF OCCURRENCE OF IRON ORES IN THE EKERSUND-SOGGENDAL DISTRICT.

1, Labradorite rock ; 2, schlieren of ilmenite ; 3, ilmenite-norite dykes.

rich in olivine instead of hypersthene. The rocks forming the Taberg complex consist of gneissose granites, olivine gabbro, which has locally given rise to amphibolites and hornblende-schists owing to the shearing stresses to which it has been subjected, and a magnetite-olivinite which is the ore-bearing mass. There is reason to believe that they were all derived from the same magma, which probably differed but little from the olivine-gabbro in character.

The gabbro, or, rather, the chief outcrop of gabbro, forms a lens-shaped mass about a mile and one-fifth long, and nearly half a mile in width. It completely

surrounds the magnetite rock, which has a maximum length of four-fifths of a mile, a width of 485 yards, and rises to about 400 feet (Fig. 7).

FIG. 7.—MAP OF THE TABERG DISTRICT.
(AFTER TÖRNEBOHM.)
Scale, 2½ inches to 1 mile.

The ore contains 43 to 45 per cent. of ferric oxide (Fe_2O_3), with a relatively small percentage of titanium

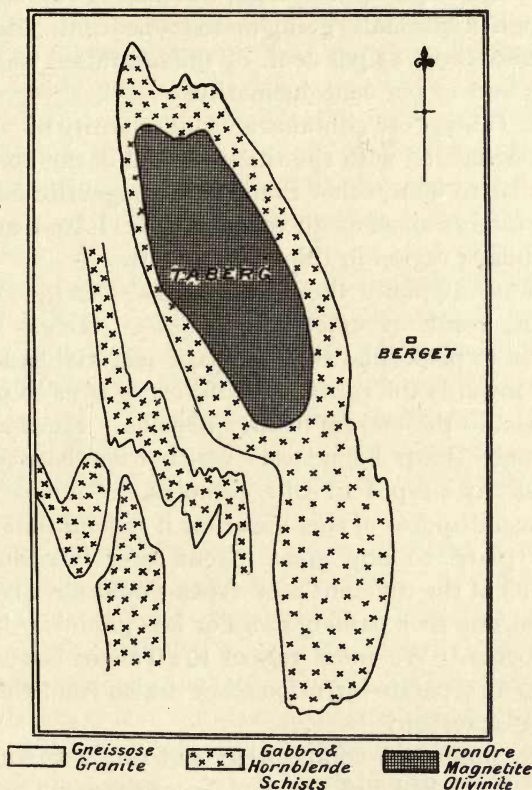oxide, being only 6·3 as compared with 44 per cent. in some of the Ekersund-Soggendal ores. A most important feature of the Taberg ore is the very small percentage of phosphoric acid, which only reaches 0·12, although occasionally going up to 1·5 per cent. Between 1891 and 1895, 83 per cent. of the ore raised was magnetite, and 17 per cent. hæmatite.

The Taberg ore contains a small quantity of vanadic acid, segregated with the titanium, and in this character is similar to many other titaniferous magnetite deposits, such, for instance, as those of Rhode Island and the Adirondack region in the United States.

It was originally thought that the Taberg complex was the result of differentiation of an olivine gabbro magma in place, and that the basic material had segregated towards the centre, instead of, as is more usually the case, to the margin of the intrusion. However, the extremely sharp boundaries which exist between the various rock-types in this complex, in almost every instance, disposes of this idea ; for if differentiation had taken place to any great extent after intrusion, the margins of the different rock-types would have been ill-defined, one rock passing more or less gradually into its neighbours. We must regard the Taberg ore and the gabbro as separate intrusions, but drawn from the same igneous reservoir.

Ores similar in composition and origin to those of Taberg and Ekersund-Soggendal occur at many localities in Southern Scandinavia, such as at Langö, Gomö, etc., and in Arctic regions similar occurrences are met with. At Lofoten, in Northern Norway, and Valimäki, in Finland, a basic magma has yielded segregations of magnetite-olivinite similar to that described above.

In South Africa, in the Transvaal region, is a great igneous complex known as the Boschveld Plutonic Series. It consists of a great group of igneous intrusions, due to the differentiation of a magma before intrusion, which range from serpentines (probably altered peridotites) to granites; olivine and hypersthene gabbros have given rise to rich segregations of very pure iron ore, while the ultrabasic rocks are associated with segregations of chromite (p. 53). So far the study of the relationship of these ores to the parent rock, and the various rock-types to one another, is far from complete, and most interesting results may be expected in the future from a closer investigation of this series.

In the New World, in the United States, in New Jersey, Minnesota, Wyoming, the Adirondacks, and in the Norian areas of Quebec and Ontario in Canada, occur masses of gabbro and allied rocks of the gabbro and norite families which have yielded segregations of titaniferous iron ores due to differentiation before or after intrusion.

In the Adirondack region, the largest ore bodies are met with in rocks, chiefly composed of labradorite felspar with a little hypersthene, olivine, or augite, which may be regarded as gabbros or norites, very poor in the ferromagnesian constituents. This labradorite rock, to which the name 'anorthosite' has been given, bears a very close resemblance both in composition and mode of occurrence to the labradorite ore-bearing rocks of Southern Scandinavia.

Masses of a dark basic gabbro are most numerous in this region, and have yielded segregations of ore. It is probable that the gabbros and the anorthosites were derived from separate magma basins, and are themselves

not the products of differentiation of the same magma, although both are more than usually rich in calcium-bearing silicates. The anorthosite and gabbro masses are intruded chiefly into gneisses and crystalline lime-stones; the ores occur in a manner identical with those of Taberg, Ekersund, and other areas in Sweden and Norway, either as basic patches and strings in the anorthosite, as segregations from the dark basic gabbros or norites, or as very rich basic dykes, like some of those in Scandinavia, which were intruded subsequently to the gabbros.

The olivine, hypersthene, and augite in the labradorite rock, and also in the gabbro, has almost always under-gone partial reabsorption, with the formation of a halo of garnet.

The ores are titaniferous magnetite and ilmenite, chiefly the former, the percentage of iron varying from 60 to 30, and the titanium dioxide from 5 to 14. Of course, some of the iron exists as silicate in the hypersthene, etc., and is not recoverable as metal. Sulphidic segregation (p. 61) is generally not well dis-played by these rocks, especially by the gabbro-masses; and in this feature the ores are more like the Taberg segregations than those of Ekersund. Sulphur is, in fact, hardly ever present in the ore in a greater quantity than 1 per cent.

Another point of resemblance between the Adirondack gabbro-ores and those of Taberg is that in almost every instance there has been a segregation of vanadium oxide with the titanium, the proportion of vanadic oxide (V_2O_5) varying from 0·1 to 0·3 per cent.

The best-known of numerous localities in these mountains where gabbroic rocks occur are chiefly near

Elizabeth Town and Westport. Here the ore exists as basic seams and patches in a hypersthene gabbro, sometimes olivine-bearing, which contains garnets around the bisilicates, and some spinel. The transition from the ore to the parent rock takes place quite gradually, but in a short space, and this is probably due to the partial reabsorption of the ore body by the gabbro. The ore contains some ferromagnesian silicates and a green glass, while in almost every instance vanadic oxide is segregated. It is poorer in apatite than the rest of the rock, but the percentage of sulphur, though small, is greater than in the gabbro itself.

The chief masses of the labradorite-rock, anorthosite, occur in the district of Lake Sandford and Calamity Brook. The ores are titaniferous magnetite and ilmenite, and they are very closely allied to those of the Ekersund-Soggendal district. They occur as streaks and dykes of nearly pure titaniferous iron ore, mixed with a very little ferromagnesian silicate, and as basic patches often existing well inside the intruded mass.

The ore-bearing dykes of Calamity Brook, Lake Sandford, and Iron Mountain deserve special mention, on account of their being separate intrusions, and the fact that they are more or less restricted to the labradorite magmas ; also on account of the great similarity they bear to the dykes associated with the labrodorite rocks of Sweden.

With regard to the origin of these ores, it is evidently due to the differentiation of a gabbro or norite magma before intrusion, and may perhaps be explained by the supposition that, as the magma began to cool, the titaniferous ores, on account of their insolubility, commenced to crystallize out from the still-molten mother-

liquor. When the ores had formed considerable aggregates, the whole was intruded in higher regions of the earth's crust, and under these conditions the segregated ore bodies could take up any position in the resulting rock. Almost the same result, however, could be brought about by the magma separating out into two magmas of extreme types, and this, perhaps, offers the better explanation of the ultrabasic ore-bearing dykes (p. 38).

Iron Ores from Syenite Porphyries.—A few cases are known in which valuable iron ores have been segregated by rocks of this type. The ore is usually magnetite, with little or no titanium ; but the percentage of phosphoric acid rises to a much higher figure in these rocks than in the gabbros and norites already described, and the amount of phosphorus is in some instances sufficiently high to render the ore of very small value.

Two important areas of iron ores which are associated with porphyries are the Swedish province of Norbotten and the Ural Mountains.

In the province of Norbotten, which lies about 67° 50′ north latitude, the chief ore deposits occur at Kirunavaara and Luossavaara. They form two well-marked parallel ridges, rising in a striking manner from the lower surrounding country, and running north and south, Kirunavaara being the more southerly of the two, and Luossavaara being a little to the north and east on the other side of the lake (Fig. 8).

The ore bodies are associated with a quartz-free syenite porphyry, in which they occur as dyke-like masses, and are presumably the result of extreme differentiation before intrusion into their present position.

The porphyry has been intruded into a variety of rocks of sedimentary origin, such as conglomerates and quartzites, which form the surrounding country.

The southern mass of ore is one and a half miles in length, and has an average thickness of 230 feet. The Luossavaara mass, as far as is known, is smaller, being three-quarters of a mile long and 180 feet wide. The total ore exposed above the level of the lake, representing about 200,000,000 tons, consists almost entirely of
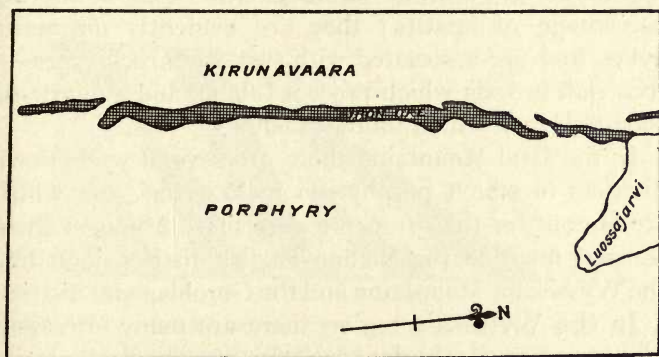
FIG. 8.—MAP OF THE KIRUNAVAARA REGION.
Scale, 1,250 yards to 1 inch.

magnetite practically free from titanium; much of it is also almost free from phosphoric acid and sulphur, but in some samples the percentage of phosphorus rises as high as 2 to 3, and in extreme cases even 5 to 6 per cent. We see, therefore, that in these masses there has also been an intense local concentration of the phosphoric acid, all of which exists in the form of apatite.

The percentage of magnetic oxide of iron (Fe_3O_4) in these ores reaches as much as 96·25 per cent., which,

with 1·82 per cent. of Fe_2O_3, represents 70·8 per cent. of metallic iron.

The two ore-masses described above are extremely important ; they form two of the largest in Europe, and compare very favourably with any in the United States, both on account of their size and the general high value of the ore they yield.

Another locality, also in Swedish territory, is Gellivara in North Sweden. The ores are similar to those of Kirunavaara, occuring as magnetite with a varying percentage of apatite; they are evidently magmatic dykes, and are associated with two other rock-types—a rock rich in soda which precedes them, and a quartzose soda-rich rock which follows them.

In the Ural Mountains there are several well-known districts in which porphyritic rocks occur, and which are famous for their iron ore deposits. Amongst these we may mention the Nizhne-Tagilsk district, including the Wyssokaia Mountains and the Goroblagodat district.

In the Wyssokaia region there are many intrusions of quartz-free porphyries consisting of orthoclase, plagioclase and augite, or augite converted into hornblende. The segregations from these masses are largely magnetite, existing as irregular patches and veins which pass insensibly into the surrounding rock. The ores therefore seem to have been formed simultaneously with the igneous rock, and are not the result of a subsequent intrusion of the more basic part of a differentiated magma. They are distinguished by their purity and good metallurgical qualities, being practically free from sulphur, and containing not too great a percentage of phosphoric acid. The magnetite of these ores has generally undergone secondary changes, resulting in

the mineral martite, which is abundant all through the Tagilsk district.

The Goroblagodat district offers very good examples of iron ores existing as segregations from syenitic magmas. The rocks of the Mount Blagodat region are similar to those of Wyssokaia, but present a slightly greater variety, ranging from true augite syenites to fine compact orthoclase rocks. The figure below shows the mode of occurrence of the ore bodies, and it will be seen that they exist in several well-marked dyke-like
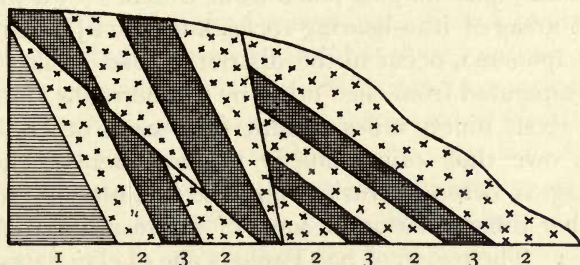
FIG. 9.—DIAGRAMMATIC SECTION TO ILLUSTRATE THE MODE OF OCCURRENCE OF IRON ORES IN THE MOUNT BLAGODAT REGION.

1, Epidote-garnet rock; 2, porphyry; 3, iron ore.

layers, making a fairly big angle with the horizontal. They are separated from each other by the syenitic rocks, and their margins are well defined. The rocks as a whole have undergone a good deal of metamorphism, giving rise to such minerals as garnet, epidote, etc., and the district has been affected by many displacements subsequent to the formation of the ore.

In North America the iron ores of Iron County, Utah, are partly due to segregation from igneous rocks, and partly to metasomatic replacements (p. 240) and

secondary enrichments in the surrounding rocks. The ore of igneous origin consists of magnetite with a low percentage of phosphoric acid, and occurs as nearly vertical dykes in a hornblende porphyrite. In mode of occurrence these masses are similar to those of the Goroblagodat region.

Iron Ores from Nepheline Syenites.—Nepheline syenites and their satellitic differentiation products are a dominant feature of some of the Continental coastal ranges. But as regards segregations of iron ore, the best examples may be taken from Brazil. Two important areas of iron-bearing rocks, known as Jacupiranga and Ipanema, occur in the district of São Paulo; they are separated from each other by the Serra do Mar, and are about ninety miles distant from each other. The ores owe their origin chiefly to the differentiation of a magma before intrusion, but also in a measure to the further differentiation of some of the resulting rocks in place. The region of São Paulo is one of clay slates and phyllites, cut by a great variety of intrusive rocks all rich in alkalies, and include such types as orthoclase-pyroxene, orthoclase-nepheline, and plagioclase-nepheline rocks, with teschenites, vogesites, etc. From the family resemblance presented by these intrusions and other considerations, we are led to regard them as the products of differentiation of a magma allied to that of a nepheline syenite. The chief ore-bearing rock is a pyroxenite, occurring in bosses and dyke-like masses, and consisting of a violet titaniferous augite with magnetic and titaniferous iron ores. Locally the iron oxides predominate to such an extent that the pyroxene practically disappears, and the rock becomes almost a pure ore.

Several of the ore-bearing pyroxenites contain nephe-

line, especially that to which the name 'jacupirangite' has been given, but with the prevalence of nepheline magnetite becomes less common, while several other accessory minerals, such as perofskite and apatite become less rare.

A tantalo-niobate occurs associated with some of the ores, and is interesting as being analogous to the segregation of the vanadinates in the Taberg and Adirondack gabbros.

From a consideration of the above, it will be seen that the magnetite deposits of São Paulo and other districts in Brazil have a somewhat different origin to the iron ores of other areas, and that the parent magma, through differentiation, has given rise to a series of rocks differing in a great measure from those associated with the iron ores which we have previously dealt with. A marked example of similar rocks yielding magnetite deposits may, however, be cited from Alnö, in the Gulf of Bothnia, where iron ores have been segregated by rocks having nepheline syenite affinities.

SEGREGATION OF CHROME IRON ORE.

Chrome iron ore, or chromite, in its mode of occurrence and general habit is closely allied to magnetite, but, as far as is known, is only found as a segregation from basic and ultrabasic rocks. It may be regarded as the most characteristic differentiation product of the highly basic ferromagnesian silicate magmas, such as those of the peridotites, picrites, and highly basic gabbros. All these ferromagnesian silicate rocks are most liable to alterations, which result in the formation of serpentines, and it is largely in masses of serpentine that chromite is mined.

This mineral is widely distributed, but it will suffice to mention a few localities. Perhaps the most important chromite deposits are those of the serpentine masses of Asia Minor, especially those occurring in the neighbourhood of Daghardy. The ore exists as stock or dyke-like masses, schlieren, and ultrabasic patches in serpentine formed by the alteration of peridotites and picrites.

Similar deposits exist in the region of Kraubat, in Upper Styria, where many peridotite masses occur, as segregations in serpentine in New Caledonia, in the ultrabasic members of the Boschveld Plutonic Series in South Africa, in fresh peridotites within the North Polar Circle, in Northern Norway, North Carolina, and many other districts.

An analysis of the Kraubat ore gives the following percentages:

SiO_2	...	...	...	...	4·3
MgO	...	...	...	...	9·7
CaO	...	...	...	...	6·4
FeO	...	...	...	...	9·1
Al_2O_3	...	...	...	...	13·7
Cr_2O_3	...	...	...	...	56·2

Although the British peridotites, picrites, and serpentines, as well as other basic rocks, often contain chromite, no deposits of economic value are known.

In Africa some Southern Rhodesian serpentines have yielded chromite and picotite, with traces of platinum and a small proportion of nickel and cobalt as sulphides.

SEGREGATION OF CASSITERITE.

Cassiterite (tin dioxide) is not usually met with in the oxidic segregations from igneous rocks, although it

is an original constituent of many granites and rhyolites. Should tin exist in the oxidic form in an igneous magma, we should, on theoretical grounds, expect it to be segregated with the iron and titanium oxides; but from the rare occurrence of such an association, as well as the presence of fluorine- and boron-bearing minerals in most cassiterite deposits, we are forced to the conclusion that the tin in most magmas did not exist simply as a dissolved oxide, but as some other compound, such as fluoride (p. 79).

It is considered that tin in most granitic magmas existed in a fluid or gaseous state until the final stages in the consolidation of the rock-mass, where it would be deposited largely in the marginal portion of the intrusion, and would probably also invade the country rock.

Should pegmatites be formed by differentiation, they might be expected to be rich in this metal. Tin-bearing pegmatites of this character would, however, contain those minerals which are looked upon as indices of pneumatolytic action.

In the Rooiberg district (near Warmbath, Transvaal) deposits of tin ore occur which are believed to be genetically connected with metalliferous pegmatites, and not to be due to pneumatolytic action. The assumption is, that some of the tin ores were deposited as an extreme hydrothermal phase of the pegmatites. The tin ore is found both in a red pegmatitic granite (with which is associated a copper vein remarkable for its paragenesis), and in the felspathic quartzites and shales of the Upper Devonian (Pretoria Series ?), among which the igneous rocks of the district were intruded. The pegmatites occur near the margin of

the granite, and consist of stanniferous quartzose and felspathic varieties; near them the granite contains fluorspar.   The copper lode is believed to be connected with the pegmatite-phase of intrusion, and consists of quartz, felspar, muscovite, siderite, calcite, fluorspar, and copper and iron pyrites.   The presence of specular iron ore in small quantities in the lodes, and separately in quartz veins, is of interest.   The extreme hydrothermal phase is supposed to be answerable for the metasomatic replacements of quartzite by tin ore, described on p. 298.

The granitoid rock of Etta Knob, in South Dakota, which is so rich in cassiterite, has been regarded as showing marginal segregation of this mineral.   We cannot, however, accept it as an example of true segregation such as we have considered previously. The outer zone of the granitoid mass differs considerably from the rest of the rock, is highly altered in character, and contains abundant fluorine-bearing minerals, such as spodumene, etc.   This deposit more probably results from pneumatolytic processes acting on the margin of the rock-mass during the later stages of consolidation.   A similar coarse pegmatite occurs in Texas (Llano County), and contains many rare radioactive minerals, such as gadolinite, but, unlike the Etta Knob pegmatite, is non-stanniferous.

An interesting example of what appears to be a true oxidic segregation of cassiterite has lately been described by the Geological Survey from Ross-shire. The ore occurs in a foliated granite gneiss as streaks and veins 100 to 250 yards in length, and 10 to 15 yards in width; it consists chiefly of magnetite, with from 3 to 5 per cent. of cassiterite, and, as we should expect

in any true segregation of cassiterite, there is a complete absence of tourmaline and other minerals of pneumatolytic origin.

The relation of the ore-masses to the rest of the gneiss is obscure on account of the shearing and faulting which the district has undergone; and although magnetite occurs disseminated through the country rock, cassiterite has as yet not been detected.

Although the ore is most probably a segregation, we must not lose sight of the possibility that these veins might have belonged to the sediments of the Moine Series, which as the result of profound metamorphism have been converted into granulitic gneisses.

A somewhat similar occurrence appears to be that of Nurunga, in Bengal, India, where tinstone is associated with magnetite, black mica, and felspar, in lenticular beds in gneiss. The origin of the ore is uncertain, but the tin may possibly be connected with the pegmatite veins which traverse the gneiss.

Cassiterite occurs as an original constituent of a few granites and acid volcanic rocks (*e.g.*, Banka and Billiton Islands), diffused more or less uniformly through the rock-masses, but particularly as inclusions in mica. It seldom occurs in sufficiently large quantities to be of any direct economic value, but such rocks may yield rich alluvial deposits. Tin-bearing granites are usually characterized by the presence of tourmaline and lithia-bearing mica.

SEGREGATION OF ALUMINA AS CORUNDUM.

Corundum cannot truly be regarded as an ore, but the mineral is of such economic importance as an abrasive agent, and so well illustrates the processes of

segregation and metamorphism, that it has been found desirable to include it in this work.

Although many of the corundum deposits of Central Europe, India, and South Africa, are of metamorphic origin (p. 344), a certain number in other parts of the world result directly from the differentiation in place of basic igneous magmas, and those of the United States are especially instructive. True segregations of corundum occur in the Appalachian region of the United States, and are yielded in all cases by rocks rich in magnesia and iron, and relatively poor in silica.

The greater number of corundum segregations are from peridotites and serpentines, a few from norites, and a still smaller number from amphibolites formed from the pyroxene-bearing rocks by the processes of dynamic metamorphism. The corundum forms an integral part of oval and lenticular intrusions of these rocks occurring in a metamorphic area largely composed of gneisses and schists. The peridotite masses of the United States, in which corundum has been found in quantity, range from the central district of Alabama northwards to the Gaspé Peninsula on the Gulf of St. Lawrence. They are especially frequent in North Carolina and Georgia; others occur in Connecticut and Massachusetts, and norites are mined in the neighbourhood of Peekskill in the State of New York. In every case, the concentration of the ore has taken place at the margin of the rock-mass in the cooler zone, and thus occupies a position analogous to that of some of the iron ores described above, and most of the nickel-bearing segregations of Norway and Canada, to be described later. The figure given below shows the general position occupied by the corundum ore with

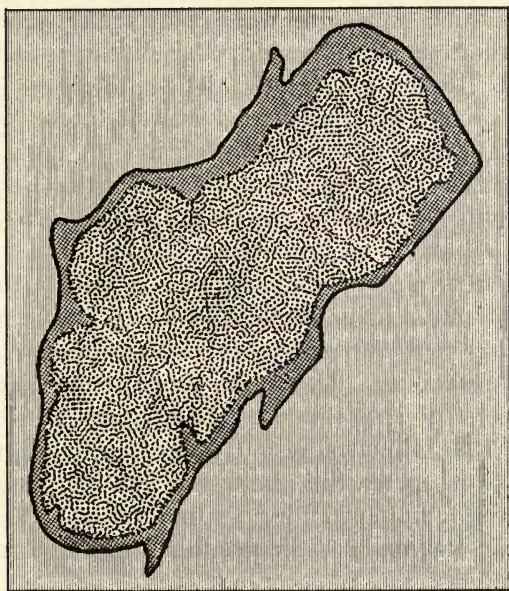reference to the parent peridotite mass, and is accompanied by a section showing the relations in depth.

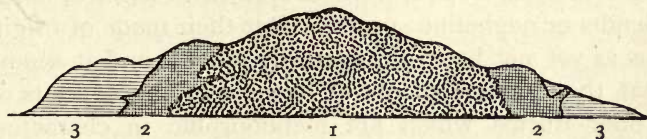FIG. 10.—MAP SHOWING THE OCCURRENCE OF CORUNDUM AS A DIFFERENTIATION PRODUCT OF PERIDOTITE.

FIG. 11.—SECTION ACROSS FIG. 10.

1, Peridotite; 2, corundum; 3, country rock.

The corundum ores of igneous origin differ in several ways from those formed by the thermal metamorphosis

of sediments, and should be readily distinguished; for besides the marked differences in the mode of occurrence, there is usually a complete absence of true metamorphic minerals, such as cyanite, which play such a prominent part in the corundum rocks of Burma, Siam, and other districts.   In the case of the peridotites, there is little doubt that the alumina was dissolved in the original magma at the time of its intrusion into the country rock, and that it separated out together with other rather insoluble oxides, such as chromite and magnetite, at an early stage, as the mass commenced to cool.

It has been proved that alumina is soluble to some extent in molten magnesium silicate, and if the magma has no excess of magnesia, then all the alumina crystallizes as corundum.   If, on the other hand, there is a slight excess of magnesia over the magnesium silicates, some of the alumina will combine with that, and crystallize as spinel, the remainder forming corundum. It is therefore not surprising to find spinel segregrated from basic magmas rich in magnesia, and occurring as a frequent associate of corundum.

In Canada, supposed original segregations of corundum occur in Ontario, and have been derived from rocks ranging from a normal syenite to a mica, hornblende, or nepheline syenite.   But their mode of origin has as yet not been satisfactorily proved, and it seems that they present points of likeness to the deposits of Upper Burma which are metamorphic in character. It is most probable that true segregations of corundum will be found to be restricted to the more basic plutonic masses representing the magmas rich in magnesium silicates.

Corundum may be formed in some instances by the

absorption of aluminous material by an igneous magma on its passage through a sedimentary series of rocks, and the subsequent crystallization of the excess of alumina on cooling. The action between the igneous rock and sediment is, however, generally quite local, and takes place within narrow limits; it is doubtful whether the formation of corundum in such cases should be regarded as a true segregation, for it seems more natural to regard it as the outcome of a metamorphic process identical with that which gives rise to the corundum in masses of sediment caught up and included, without absorption, in an igneous magma.

SEGREGATION OF METALLIC SULPHIDES.

Segregations of sulphides of certain metals, as well as small quantities of arsenides, are highly characteristic of several types of igneous rocks, and are clearly the direct result of the differentiation of the magma either after or before intrusion. By far the greater number of sulphidic segregations are yielded by basic igneous rocks, rich in such ferromagnesian minerals as hypersthene and other orthorhombic pyroxenes, and with a silica percentage of not more than 55. The sulphidic compounds are apparently soluble in fused silicates at high temperatures. The metallic sulphides which characterize this class of segregations are those of nickel, cobalt, copper, and iron; there is usually some titanium, and occasionally the percentage of oxidic iron ores may reach a considerable figure in segregations which form the connecting links between the oxidic and sulphidic types. Very occasionally some of the rare metals, such as platinum, iridium, rhodium, and palladium, are found associated with the metallic

sulphides, but they exist only as arsenides, as far as is at present known. In the sulphidic segregations from basic igneous rocks there is generally an absence of lead, zinc, silver, antimony, bismuth, and tin, and arsenic is of rare occurrence. Molybdenum is not an uncommon constituent of certain granites.

Should several metals exist as sulphides in one and the same magma, it has been found that they have a definite order of crystallization, and therefore a varying degree of concentration ; for instance, suppose a magma to contain nickel, cobalt, iron, copper in the form of sulphides, and some titanium, on cooling, pyrites rich in cobalt would be the first mineral to crystallize, and would be segregated with the titanium. The pyrites would be followed by nickeliferous pyrrhotite, pyrrhotite, and copper pyrites. Pyrrhotite appears to favour those rocks rich in ferromagnesian minerals, while pyrites is not so restricted.

The concentration of sulphides is generally best displayed by magmas which have differentiated in place, and the segregations are almost always marginal in character, thus differing from so many oxidic segregations which occur as ultrabasic dykes and schlieren due to differentiation of the magma before intrusion.

Another difference of importance is that in the case of sulphidic segregations there has been no complementary segregation of the ferromagnesian silicates, as was such a conspicuous feature of many of the segregations of oxides previously described.

Rocks with gabbro affinities may be divided roughly into two overlapping groups—the one olivine-bearing, and the other containing some orthorhombic pyroxene, such as hypersthene. The olivine-bearing rocks, as well

as many of the other group also, as we have seen, are characterized by oxidic segregations; but the second group includes the norites and hypersthene gabbros, to which the chief segregations of metallic sulphides owe their origin.

Rocks which, at first sight, seem to be of a different type to those mentioned above have occasionally yielded
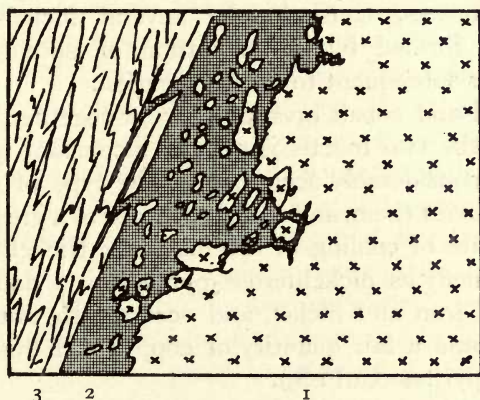
FIG. 12.—SECTION TO ILLUSTRATE THE MODE OF OCCURRENCE OF SULPHIDIC SEGREGATIONS CONNECTED WITH NORITE INTRUSIONS.

1, Norite; 2, sulphidic segregation (pyrites); 3, gneiss (country rock).

segregations of sulphides, especially of nickel and cobalt. They are chiefly what may be termed 'gabbro-diorites,' but they were evidently pyroxenic rocks originally, and have been altered by metamorphism of a regional type, which has developed hornblende (uralite) at the expense of the pyroxene.

SEGREGATIONS OF NICKEL AND COBALT.

The nickel and cobalt ores that occur as segregations from norites and other hypersthene-bearing rocks, may be divided into two groups:

(*a*) Sulphidic ores, consisting of the iron-nickel sulphides, pyrrhotite, and nickeliferous pyrites, and the nickel sulphides millerite and polydymite.

(*b*) Silicates, consisting of several nickel-bearing silicates formed by the alteration of sulphides and arsenides subsequent to the segregation.

Nickel and cobalt invariably occur together, but the ratio of the two metals is a most inconstant quantity, varying considerably according to the type of sulphide which carries them, and being governed to a great extent by the rate of cooling of the magma. Nickel is segregated chiefly as nickeliferous pyrrhotite, a double sulphide of iron and nickel, and occurs with titaniferous iron ore and a fair quantity of copper and iron in the form of pyrites ($CuFeS_2$).

Pyrrhotite always contains 2 to 5 per cent. of nickel and cobalt taken together, and should a pyrites crystallize out before the pyrrhotite, it is generally richer in cobalt than in nickel; thus, while in the pyrrhotite the ratio of nickel to cobalt is as 10 to 1, in the pyrites it is reversed.

The iron sulphide segregations, containing a high percentage of nickel and cobalt (15 to 20 per cent.), do not carry these metals combined with pyrites, but as the sulphides millerite and polydymite, containing 5 to 10 per cent. of nickel, intimately mingled with the pyrites.

The average nickeliferous ores contain about 1 per

cent. of Co to 6—8 per cent. of Ni, but in some cases the ratio is as 1 to 3 or as 1 to 10 or 15. This variation is due, as before stated, not so much to the original content of the magma, as to the degree of concentration dependent on the rate of cooling of the magma as a whole.

Numerous examples of sulphidic segregations of nickel and cobalt from norites may be drawn from Southern Norway and Sweden, Piedmont in Italy, Canada, and the United States of America; and other nickel ores are met with in Malaga, New Caledonia, Oregon, and North Carolina, associated with serpentines.

In the Erteli district the ore-bearing rocks form a transitional series from ordinary norites, which contain most of the ore, to an olivine gabbro without ores, and present a most instructive example of the results of differentiation. The rock-mass varies gradually from an ordinary augite- and olivine-free norite, through a diallage-bearing but olivine-free norite, to a hypersthene gabbro; which gives place to an olivine norite, and ultimately to a hypersthene-free olivine gabbro. The olivine is segregated on the one hand, and the rhombic pyroxene with the nickel ores on the other. At Klefva, in Smaland, the rock-masses vary from a hypersthene gabbro to a pyrrhotite norite, and are identical in original character to those described above, but subsequent changes have resulted in the transformation of many of the rocks from gabbros to uralites.

Good examples of the marginal segregation of nickeliferous pyrites from norite and gabbro-magmas are also furnished by the following three localities—the Nysten and Bamle Mines, the Meinkjaer Mines, and the Skang Mine.

The ore is magnetic pyrites with 5 to 6 per cent. of nickel and cobalt, and is met with at the junction of the gabbro-masses with the hornblende-schists, etc., into which they are intruded.

Although the ores almost always exist at the periphery of the rock-masses, veins and patches occur in some cases. These patches are sometimes composed of pyrrhotite norite, sometimes of extremely pure pyrites, and occur well within the gabbro-masses.

Another well-known European example is that of Varallo in Piedmont. The mica schists and gneisses of the Monte Rosa neighbourhood are broken through by masses of norite, which are sometimes without olivine and augite, but at other times contain these two minerals.

The ore consists of a pyrrhotite norite, as in the case of the Scandinavian masses; it contains 4 to 5 per cent. of nickel and cobalt, and occurs at the contact of the igneous rocks with the schists and gneisses, into which they have been intruded. Two well-known mines are the Cevia and the Sella-Bassa.

The nickel ores of Canada and the United States occur in three ways—either as masses fringing the intrusions, as impregnations through the rock-mass, or as veins filled by solutions subsequently to the intrusion of the magma. The last two types are not segregations, but belong to a different category, and therefore will not be discussed here, but in their place in a subsequent part of this volume. In Canada the ores of Sudbury have received the most attention, and although several theories have been propounded to explain their origin, none seems so satisfactory as segregation.

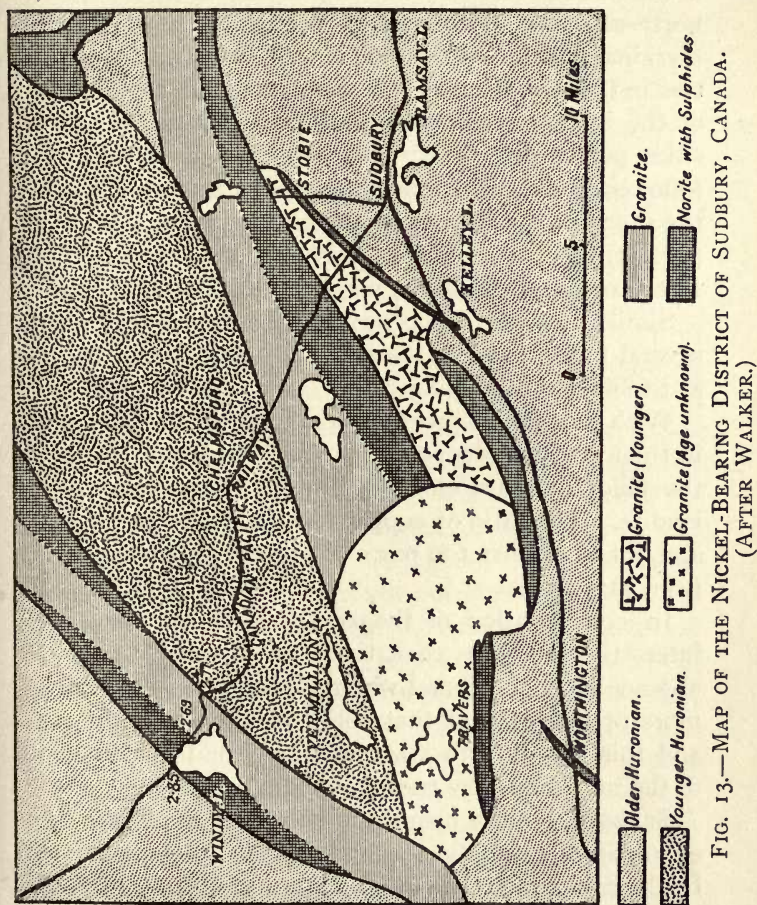The ore-bearing rocks without exception are norites or derivative diorites (uralites), and have been differen-

FIG. 13.—MAP OF THE NICKEL-BEARING DISTRICT OF SUDBURY, CANADA. (AFTER WALKER.)

tiated from ophitic quartz-bearing gabbros and pegma-tites. These masses throw off occasional norite dykes,

which yield nickel ores on their margins, and small bosses of norite also occur. The most interesting mass is the one shown in the accompanying map as ranging north-east and south-west of Windy Lake. Here the marginal position of the ores is well seen, and the variation in the rock-mass may best be studied. The interior of the igneous masses consists of a pegmatite with a silica percentage of 69·7 and a specific gravity of 2·69; followed towards the margin, the silica falls to 49·9, and the specific gravity rises to 2·85, as the rocks loose their pegmatitic character and pass gradually into norites. In the ore itself the silica percentage is less than 10.

Similar masses occur nearer to Sudbury itself, and several nickel-bearing norite dykes may be noticed, as at Stobie and Worthington.

With the nickel is segregated a fair quantity of copper in the form of chalcopyrite, and some magnetite, so that the chief ores are chalcopyrite, pyrrhotite, and pentlandite. The ratio of copper to nickel is most variable, and, taken against 100 parts of copper, the nickel varies from 21·5 to 170.

In consideration of the origin of these ores, it is interesting to note that there is almost a complete absence of underground water in the mines, making it more or less evident that solution has played no part, and this is still further borne out by the fact that none of the minerals show traces of hydration.

Sudbury, besides furnishing us with some of the best examples of sulphidic segregations, is also characterized by the comparatively rare segregations of arsenides, the most remarkable of which is sperrylite, essentially a platinum arsenide, having the theoretical composition $PtAs_2$.

A detailed analysis gives the following figures, and reveals the fact that other rare metals besides platinum are represented :

					Per Cent.
Pt	...	...	...	...	54·47
Rh	...	...	...	...	0·76
Pd	...	...	...	...	trace
As	...	...	...	...	42·23
Sb	...	...	...	...	0·54

Gold, silver, and some tin, have also been detected in the Sudbury ores, and platinum in the nickeliferous ores of Klefva. In the United States one of the most famous nickeliferous districts is that of Lancaster Gap, in Pennsylvania. Here we have a most beautiful example of differentiation in place, for the intrusion, which is almost symmetrical in form, rapidly becomes more basic towards the margin, along which the nickel ores form an almost continuous zone. The igneous mass consists of amphibolite, a uralitized norite, intruded into mica schists, and the ores of pyrites and nickeliferous pyrrhotite. Analogous to the segregation of sulphides and arsenides from the Sudbury norites mentioned above are the segregations of nickel arsenide connected with the Malaga serpentines. These rocks vary from true peridotites, through picrites, to norites, and the ores change from nickel silicates near the surface to nickel arsenide in depth. They are associated with a good deal of chromite, which in the richer ores is seen to have been segregated at an earlier period than the nickel arsenide which fills the interstices between the chromite crystals. The nickel silicate ores contain from 1 to 20 per cent. of nickel, and are evidently derived from the arsenide, which is a true differentiation product, by the action of circulating waters.

Districts in New Caledonia, Oregon, and North Carolina, all yield nickel silicates associated with olivine rocks, such as peridotites, now converted into serpentines. It is quite possible that these ores have been derived from segregated sulphides and arsenides, but as yet the unaltered minerals have not been met with.

SEGREGATIONS OF COPPER AS PYRITES.

Little need be said regarding the segregation of copper ores from igneous magmas, for their mode of origin is identical with that of nickel and cobalt, and they often accompany those metals in considerable quantity. Copper ores as sulphidic segregations are not common, however; most of the rich deposits have a different origin, and exist either as precipitations from solutions or as pneumatolytic and metasomatic deposits.

It has been previously stated that copper in the segregations almost always exists as the copper-iron sulphide chalcopyrite ($CuFeS_2$), and is usually associated with basic pyroxenic igneous rocks. In the Namaqualand district of South Africa, sulphidic copper ores occur associated with igneous rocks. The district is one of granite, gneisses, and schists, capped locally by sediments, and pierced by intrusions of basic igneous rocks of gabbro affinities. The ore deposits are irregular in form, and occur both in the basic rocks and in the granite. At Nabatiep the ore occurs chiefly in the basic rock as streaks and bunches, and seems to be a product of differentiation.

In the nickel-bearing ores of Sudbury, in Canada, and other regions, the percentage of copper is occasionally large, and, according to some authors, the rich copper

ores of Tuscany, Liguria, and North Italy, associated with serpentinous rocks, must be looked upon as magmatic segregations.

It is interesting to note that copper pyrites exists in fair quantity in the basic patches occurring in many granites and syenites, especially in the latter. It has been found in the basic inclusions of the Plauenschergrund syenite, where its concentration is due to the early crystallization of the sulphides from the syenite magma.

In addition, certain pegmatites in British Columbia and in the Encampment district of Wyoming contain streaks and veins of bornite which appears to be a product of differentiation.

CHAPTER III

PNEUMATOLYSIS

A GREAT many ore deposits are now recognized to be directly connected with plutonic intrusive rocks, and to have been derived from them through the agency of magmatic gases dissolved in them at the time of intrusion, and existing, therefore, at high pressure and above their critical temperature.

The conditions of pneumatolysis are those of the liberation of magmatic vapours and steam during the consolidation of the deep-seated intrusive rocks. The action is not thought to have ever occurred before consolidation to any extent, while after complete consolidation the process may be regarded as having altogether ceased.

The vapours during the consolidation of the magma played an important rôle in the extraction of the metals disseminated through it, so that in the absence of such vapours, pneumatolytic action, except in cases where the metal itself is volatile, is impossible, and ore deposits of this nature could not be formed. In such a case any metals present in the magma would remain in the rock on consolidation as accessory oxides, sulphides, or silicates, distributed through it like any other constituent mineral; or if in large quantity would become essential

constituents, or even massive differentiation products, forming deposits known as 'segregations.' The pneumatolytic action is therefore a process of extraction of metalliferous minerals by active superheated gases, in the absence of which the sulphides or oxides of the metals would have remained in the rock as ordinary constituents.

The assumption that superheated gases containing metals as volatile compounds were the main agents in the formation of certain types of ores necessarily implies that in the majority of cases the deposits occur not far from the plutonic rocks which gave rise to them, and in typical regions this so far holds true that the principal deposits are found in fissures and joints in the altered rocks of the metamorphic zone surrounding the plutonic intrusion, or in the igneous rock itself.

Although the general principles of pneumatolysis were conceived nearly a century ago, the most important contributions to the subject were made by Professor Vogt in a series of papers published between the years 1894 and 1899.* It is mainly upon Vogt's work that the classification is based.

In a general way, the mode of origin of the several classes of ores under this category is the same, yet the ores are quite distinct, and are characteristic products of the type of rock giving rise to them; and it is now well known that the metals and minerals of lodes associated with basic rocks (gabbros) and acid rocks (granites) indicate to a considerable extent the nature of the magma from which they were extracted.

Broadly speaking, the genetic classification of ore

* *Zeit. f. Prakt. Geol.*, 1894, 1895, 1898, 1899.

deposits formed under pneumatolytic conditions depends upon three things :

1. The nature of the rock giving rise to the ores.

2. The particular metals of the ores.

3. The minerals associated with the ores, indicating the nature of the gases which extracted the metals as volatile compounds from the magma.

To these gases the terms ' carriers,' ' mineralizers,' and *agents mineralisateurs* have been variously applied.

There are two broad classes of ores of pneumatolytic origin—the sulphides and the oxides—one or both of which may be secreted during the consolidation of either the acid or basic plutonic rocks ; but since each magma has its characteristic metals and ' mineralizers,' the deposit to which it gives rise will be oxidic or sulphidic according to the affinities of the metals contained in the magma and to the presence or absence of sulphur.

Thus, tin practically always occurs in the form of oxide, whether sulphur be present in the magma or not. Iron may occur either as oxide or sulphide, lead nearly always as sulphide.

In a fused condition, acid magmas, such as those giving rise to granites, although intensely hot, are considered to have been very viscous or pasty, since on intrusion among the overlying rocks they have assumed massive or bulky, instead of sheet-like, forms. These immense laccolites are generally of deep-seated origin (batholiths), and consequently all the conditions of slow cooling were present.

In basic magmas, on account of their lower consolidation points, the liberation of magmatic gases takes place at lower temperatures. Their fusibility affects to some extent the form of the intrusion.

During the cooling of the igneous masses the rocks surrounding them are thermally metamorphosed for distances varying from a few hundred feet to a mile or more, so that they, too, are in a heated condition. Although the metalliferous minerals are very sparingly distributed through the magma, they are nevertheless gradually withdrawn from it during crystallization by means of active magmatic gases, and in time are more or less concentrated in the not fully consolidated parts of the intrusion.

The next step in the process is the escape of the metalliferous gases, and concentration of the ores in the positions in which they are found. It is only necessary, then, that the means of escape should be provided, and in deposits of this nature this is invariably in fissures formed by various causes in the solid parts of the igneous rock and in the older rocks beyond.

In traversing fissures in the cooler rocks reactions took place with the liberation of metallic oxides and sulphides, and the formation of characteristic minerals through the action of the remaining gaseous material on the country-rock.

Once the magma was consolidated, the conditions of pneumatolysis ceased, and, instead of vapours, thermal mineral waters were given off. The change from the one condition to the other is gradual, but it appears highly probable that, under the cooler conditions in which liquid solutions occur, a set of substances may be deposited in fissures, which, owing to their inability to form volatile compounds, were not carried off in the earlier gaseous phase, or, at any rate, were only carried off in small quantity. At the same time, many substances which were readily volatilized under pneuma-

tolytic conditions became, under cooler conditions, stable compounds no longer capable of extraction.

This applies not only to the ores, but also to the mineralizers, which likewise have to be taken into account in treating of the origin of the deposits.

According to Brögger's researches, the stage at which the pneumatolytic action is most intense is that which follows the first possible phase of ore concentration, namely, that of magmatic segregation ; but it precedes, or is in part contemporaneous with, the third phase at which zeolites may be formed through the action of magmatic waters containing minerals in solution. In both the pneumatolytic and zeolitic phases the already consolidated minerals of the magma are liable to be altered or decomposed.

Before discussing a few typical cases, it should be noticed that ore deposits of pneumatolytic origin invariably occur as infillings of pre-existing spaces and as impregnations of the rock in their vicinity, so that the shape of the deposit is largely determined by joints, irregular fissures, faults, friction-breccias, partings along bedding planes or other spaces in the sedimentary rocks of the metamorphic zone, or in the igneous rock with which the deposits are genetically connected.

But although the form of the deposit is of great importance to the miner, the nature of the alteration which the vapours, once traversing the fissures, have effected in the country-rock, at the sides of the lode, is of considerable interest. In many cases the walls of the lodes have been so entirely altered by the vapours that they are rendered unrecognizable as part of the country-rock ; and it is by the nature of this alteration, and by the minerals in the lodes, that the origin of the

ores may be determined. In all classes of ores of pneumatolytic origin, the rock in the vicinity of the fissures, in addition to other secondary minerals, invariably contains some of the ore impregnating it to more or less extent; that is to say, some of the minerals of which the country-rock is composed are replaced by the ores, while the rest may not be altered or affected in any way.

Typical examples of pneumatolysis may be taken from the ore deposits connected with gabbros and granites respectively, and a comparison of one with the other will show that, while the minerals taking part in the action in each case are different, the general mode of origin is the same.

Ores of Pneumatolytic Origin connected with Granite and its Allied Rocks.

Normal granites are holocrystalline rocks of hypidiomorphic structure, which consist of a ferromagnesian mineral, generally biotite (but occasionally hornblende), muscovite, felspar (orthoclase, and sometimes acid plagioclase), and quartz. The percentage of free and combined silica varies from 65 to 80.

The principal allied plutonic rock is syenite, which is of less siliceous character.

The family of fine-grained porphyritic rocks of similar chemical composition to normal granite, but occurring in the form of dykes or sheet-like intrusions, are not directly connected with ore deposits of pneumatolytic origin, owing to their small bulk and their consequent inability to supply enough material for the production of ore deposits, and to a certain extent to the conditions

of rapid cooling to which their fine-grained character is due. The principal amongst these are the quartz porphyries, or elvans. Indirectly, however, their connection with the granite on the one hand, and the ore deposits on the other, is of great interest, as it is a common feature in some of the typical regions for the principal metalliferous deposits to occur in an area which had previously been a focus for dyke intrusions.

The ores characterizing typical pneumatolytic deposits in granites are those of cassiterite, and wolfram and scheelite, any of which may be accompanied by sulphidic ores of copper, iron, and arsenic in large quantity. In less quantity, but not uncommonly, there may be ores containing the metals bismuth, or even antimony, zinc, cobalt, occasional nickel, manganese, molybdenum, uranium, and gold ; still rarer, minerals containing tantalum and titanium. In some instances argentiferous galena occurs with the tin, tungsten, copper, arsenic, or other ores of undoubted pneumatolytic origin, and its presence, although exceptional, may be regarded as one of the types connecting the *filons stannifères*, or cassiterite veins, and the *filons plombifères*, or lead veins, since the conditions under which most lead veins are formed, although connected with after-eruptive actions, belong to the last phases of igneous consolidation. In Bolivia, however, the sulphides of lead and some other metals occur to the exclusion of copper ores, and may be contemporaneous with the tinstone.

It should be remarked therefore that, according to the metals originally contained in the eruptive magma, the lodes may contain all or only one of the aforementioned metals.

NATURE OF THE VAPOURS WHICH EXTRACTED AND DEPOSITED THE MINERALS OF CASSITERITE VEINS.

It was shown early in the last century that all tin lodes were characterized by the presence of minerals containing fluorine. It was inferred, and, by experimental research, proved, that fluorine was able at high temperatures to form a volatile compound with tin, which at lower temperatures in presence of steam was decomposed into oxide of tin and hydrofluoric acid.

$$SnF_4 + 2H_2O = SnO_2 + 4HF.$$
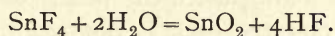
It is to the action of the latter compound that the production of fluorine-bearing minerals in the country rock is due. But, from the nature of other secondary minerals of common occurrence, there must also have been vapours containing boron, and even chlorine, carbon dioxide, and, frequently, sulphur. It is highly probable that in conjunction with superheated steam these vapours all assisted in, first, extracting the various metals from the magma during consolidation, and, secondly, in carrying them in the form of volatile compounds into fissures. The presence of silica must not be forgotten, since much quartz in tin veins was probably deposited from volatile compounds of silicon and fluorine.

$$SiF_4 + 2H_2O = SiO_2 + 4HF.$$
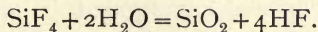
It will be seen that, although these vapours occurred together in the magma, their emanation was not necessarily simultaneous. Some veins of pneumatolytic origin are characterized by fluorine-bearing minerals, others are typified by minerals containing boron or

chlorine. The metals of this group of ore deposits exist chiefly as oxides and sulphides.

NATURE OF THE ALTERATION IN THE WALLS OF TIN LODES.

Hydrofluoric and boric vapours, boro-silico-fluorides, together with hydrofluo-silicic acid and other gaseous compounds, are able to decompose various constituents of the country-rock, with the production of new minerals. While some rocks are readily altered in this way, there are others which are practically unaffected.

Where the country-rock is not readily seen to be traversed by cracks, the microscope shows that the alteration in the walls commenced in the first place along minute cracks or lines of rifting, cleavage cracks, planes of bedding, and in interstitial spaces. The corrosion or alteration of the country-rock begun in this way is readily carried on. The minerals which are particularly attacked are felspars, micas, and argillaceous and calcareous materials. The minerals which are produced are topaz, axinite, tourmaline (brown and blue), chlorite, kaolin, green and white mica, and fluorspar; and, probably, iron pyrites, as a result of conversion of oxide of iron into the sulphide by sulphur vapours. Finally, silicification of the country-rock is so common as to constitute an important type of alteration. In special cases garnet is also formed, but this must generally be regarded as owing to a combination of contact and pneumatolytic actions.

It will be seen, therefore, that the type of alteration was determined by the nature of the vapours or solutions which traversed the fissures, while the minerals formed depended on the composition of the country-rock.

Broadly speaking, the changes in the country-rock are brought about by greisen - action, silicification, chloritization, kaolinization, etc., and depend upon the nature of the vapours.

In granite the alteration is as follows: biotite, by loss of alumina, oxide of iron, and magnesia, is changed to muscovite, with occasionally some epidote and oxide of iron. If boric acid be present, the mineral is
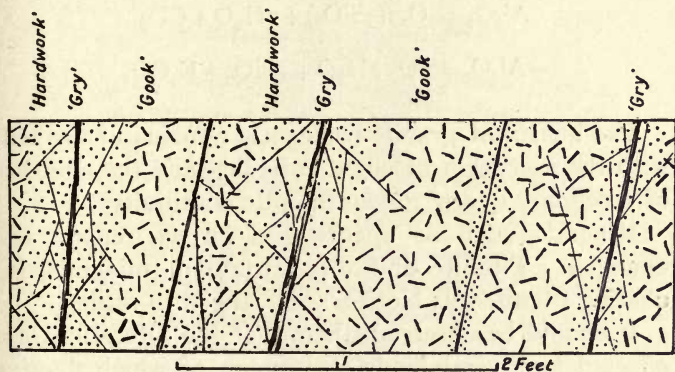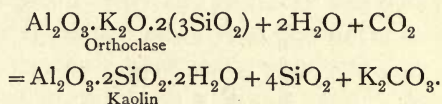

FIG. 14.—DIAGRAM SHOWING THE LODE STRUCTURE AND NATURE OF ALTERATION OF THE COUNTRY-ROCK AT THE BALLESWIDDEN MINE, ST. JUST, CORNWALL.

'*Gry*,' a tin-bearing joint or vein; '*Hardwork*,' greisen, consisting of schorl, quartz, mica, and topaz; '*Gook*,' the soft, kaolinized granite beyond the hardwork.

altered to brown tourmaline. Chlorite may be formed from biotite by the action of sulphides (propylitization), carbonic acid gas or carbonates, and frequently is associated with metallic sulphides.

The alteration of the felspar commences along cleavage planes and cracks, with the production of topaz (by fluorine), muscovite (also gilbertite and zinnwaldite), and quartz. Cassiterite frequently occurs

6

as pseudomorphs after the felspar of the ground mass or of phenocrysts. Complete silicification of the felspar is not uncommon, while in the presence of boric acid vapours blue tourmaline-needles are formed. Although topaz is considered to be occasionally altered to kaolin, the kaolinization of felspars is regarded as being mainly due to the action of carbonic acid gas which removes some of the potash and silica.

$$Al_2O_3.K_2O.2(3SiO_2) + 2H_2O + CO_2$$
$$\underset{\text{Orthoclase}}{}$$
$$= Al_2O_3.2SiO_2.2H_2O + 4SiO_2 + K_2CO_3.$$
$$\underset{\text{Kaolin}}{}$$

The quartz of granite frequently remains unaffected, with the exception of slight corrosion and the addition of secondary quartz grown in optic continuity.

Minerals such as apatite and zircon remain unchanged. Titanite and other titanium minerals, including titaniferous biotite, are changed to rutile.

It should be observed, then, that the alterations are effected by several kinds of vapours, of which fluorine invariably belongs to the earliest emanations, while carbonic acid gas, hydrogen sulphide, and boric acid, may belong to either the earlier or later emanations.

The extent of alteration in the sedimentary rocks of the contact-zone depends partly on their composition. In finely banded rocks consisting of alternations of sandy and argillaceous films, it is the argillaceous material which is principally affected by the vapours, and in particular by boric acid and fluorine. The principal alteration when boric acid was present is tourmalinization along the argillaceous films, for several inches away from the vein (Fig. 15). The altered rock is extremely hard, and, as all the previously formed

folds or contortions in the rock are preserved, it has a remarkable appearance.

In some of the tourmalinized sediments from the neighbourhood of Roche Rock, in Cornwall, the tourmaline of these mud films is of dirty brownish-grey or blue colour, with many impurities. With it there frequently occurs cassiterite.
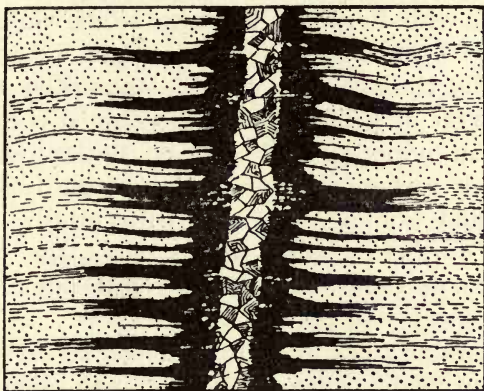

FIG. 15.—VEIN OF TIN-STONE, QUARTZ, AND TOURMALINE TRAVERSING PALÆOZOIC SLATES CONSISTING OF ALTERNATE BANDS OF ARGILLACEOUS AND SILICEOUS MATERIALS, BELOWDA BEACON, CORNWALL. (NATURAL SIZE.)

The argillaceous bands are replaced for several inches on either side by tourmaline, while the siliceous bands are unaffected.

In originally calcareous metamorphic rocks, such as calcsilicate-hornfels, the production of axinite instead of tourmaline takes place. This mineral occurs in abundance in the altered calcareous bands of the Lower Devonian rocks on the north of the St. Austell granite mass, in Cornwall, in which locality tin veins are also found.
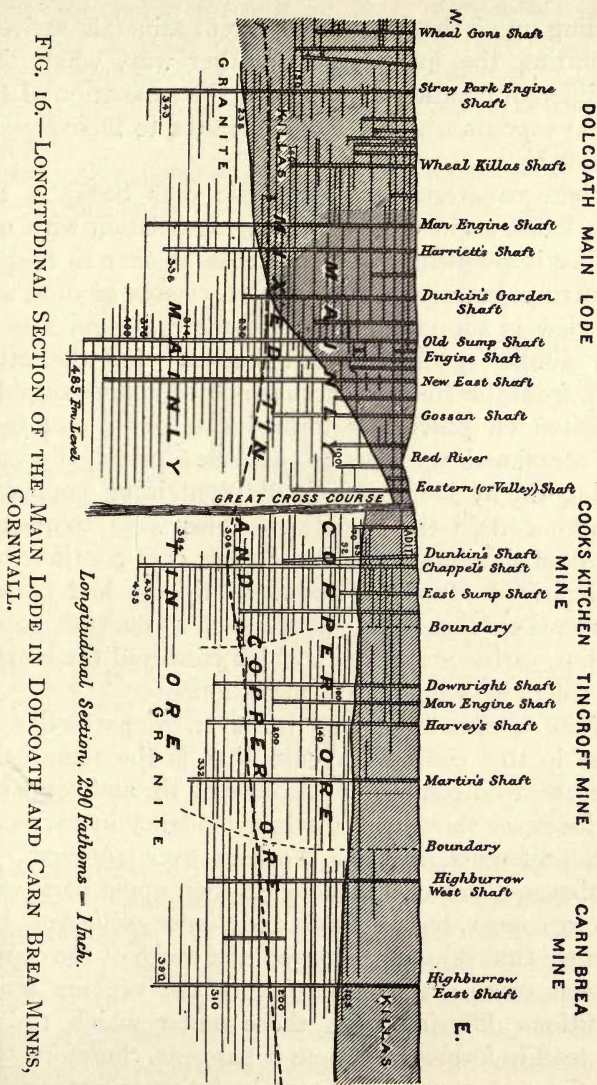
In the older basic intrusive rocks near the granite the effects of pneumatolysis are also well marked. In the Cornish greenstones axinite is developed, and is associated with veins of garnet and epidote. The occurrence of garnet veins appears to be due to contact alteration, with addition of siliceous materials by solutions. On a large scale in Arizona garnet and copper ore are found in association at the contact of limestone with dioritic and granitic rocks, while similar occurrences are known in Hungary and Transylvania, Servia, the Urals, New South Wales, and Queensland. In the West of England numerous similar occurrences have been noticed; at Botallack, tinstone is found in sheared garnetiferous greenstone; near Lostwithiel copper and iron pyrites occur with massive garnet. On the northern margin of Dartmoor the ores are seen in connection with garnet at the Belstone Consols Mine.

The garnetization of non-calcareous rocks has been noticed in Idaho, where at White Knob chimney-like masses of garnet have been formed along cracks in granite porphyry; the garnet appears to have been developed by the action of solutions containing iron oxide and lime on the rock.

Silicification of the walls of tin lodes is a common phenomenon, and the rock which results from this alteration is quartz which encloses chlorite or tourmaline-needles. It is this variety of rock which is known as 'peach' in Cornwall.

ORDER OF ARRIVAL OF THE MINERALS IN TIN LODES.

In tin lodes characterized by the presence of sulphides it is of interest to know at what periods in the

FIG. 16.—LONGITUDINAL SECTION OF THE MAIN LODE IN DOLCOATH AND CARN BREA MINES, CORNWALL.

Longitudinal Section, 290 Fathoms = 1 inch.

building up of the veins the different minerals arrived; or putting the question in another way, what were the different conditions governing the emanation of the several vapours which brought the ores to their present position ?

Where cassiterite and sulphidic ores occur in the same lodes, as in Cornwall, their association with one another is frequently so intimate as at once to suggest a contemporaneous origin for both classes of ores, and this view is supported in a still more general way by their similar geological distribution. On the other hand, from the frequent occurrence of copper sulphide deposited on previously formed cassiterite, and from the occasional intersection of lodes principally containing tin by lodes principally containing copper, it is quite certain that, while the ores were frequently deposited simultaneously, the copper ores continued to be deposited after the arrival of tin ore had ceased. It is thus evident that vapours, such as fluorine, boron, sulphur, carbonic acid, etc., which conveyed the metals, had a definite sequence of emanation.

There is one more fact, however, of particular interest in this connection, and that is the remarkable zone-like arrangement of the ores of tin and copper in the lodes, as showing a distinct tendency in each case to a preference for one horizon over another.   In Camborne (Cornwall) the lodes in their upper parts were rich in copper, but in depth are almost exclusively tin-bearing; thus it may be inferred that much of the copper ore was originally deposited from the vapours under conditions differing from those under which tin ore was readily formed.   Where it happens, therefore, that the tin and copper ores are in intimate association,

it is reasonable to suppose that, even although the minerals arrived contemporaneously, the cassiterite would probably be deposited first, and so have all the appearance of having arrived before the ores of copper.

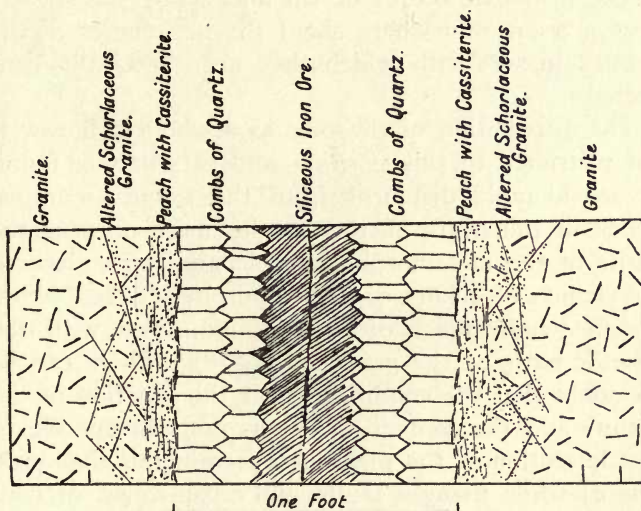On the whole, a study of the lodes of Cornwall shows the order of mineralization to be: (1) Tin ore

FIG. 17.—STRUCTURE OF A LODE AT THE BELLAN MINE, ST. JUST, CORNWALL.

and wolfram, commonly accompanied by sulphides of copper, arsenic, and iron. Stannite and scheelite occur exceptionally. (2) Sulphides of copper, iron, and arsenic, with zincblende and, rarely, sulphides of lead, silver, and cobalt. (3) Lead and silver sulphide, and iron oxides and carbonate. The rarer ores not infrequently belong to a late stage, and in some cases are quite

the last minerals to be deposited. Among these may be mentioned nickel, antimony, manganese, and uranium, some of which, however, were deposited also in the earlier phases of lode formation.

ASSOCIATION OF TIN AND COPPER ORES WITH THE METAMORPHIC ROCKS SURROUNDING THE GRANITE.

The principal bodies of tin and copper ore nearly always occur somewhere about the peripheries of the granite masses with which they are genetically connected.

The distribution of the ores as a whole is, however, not restricted to this position, and they may be found at considerable distances from the granite-margins, either in the heart of the granite-mass or near the limits of the metamorphic aureole, and particularly in the vicinity of elvans, or quartz porphyry dykes, whose presence indicates a direct communication with the interior parts of the granite (Fig. 18). There can be no doubt that the conditions near the junction of the granite and the contact-rocks was more favourable to the deposition of the metalliferous minerals than elsewhere; while fissures, faults, and crush-zones, of considerable size, affording spaces for the building up of ore bodies of great commercial value, are also commonly found in such situations.

TYPICAL EXAMPLES OF DEPOSITS OF PNEUMATOLYTIC ORIGIN CONNECTED WITH ACID INTRUSIVE ROCKS.

Cassiterite and Wolfram.—In Cornwall and Devon the tin and copper deposits are intimately associated with five large granite batholiths, two of which, in West Cornwall, are intruded among sediments of
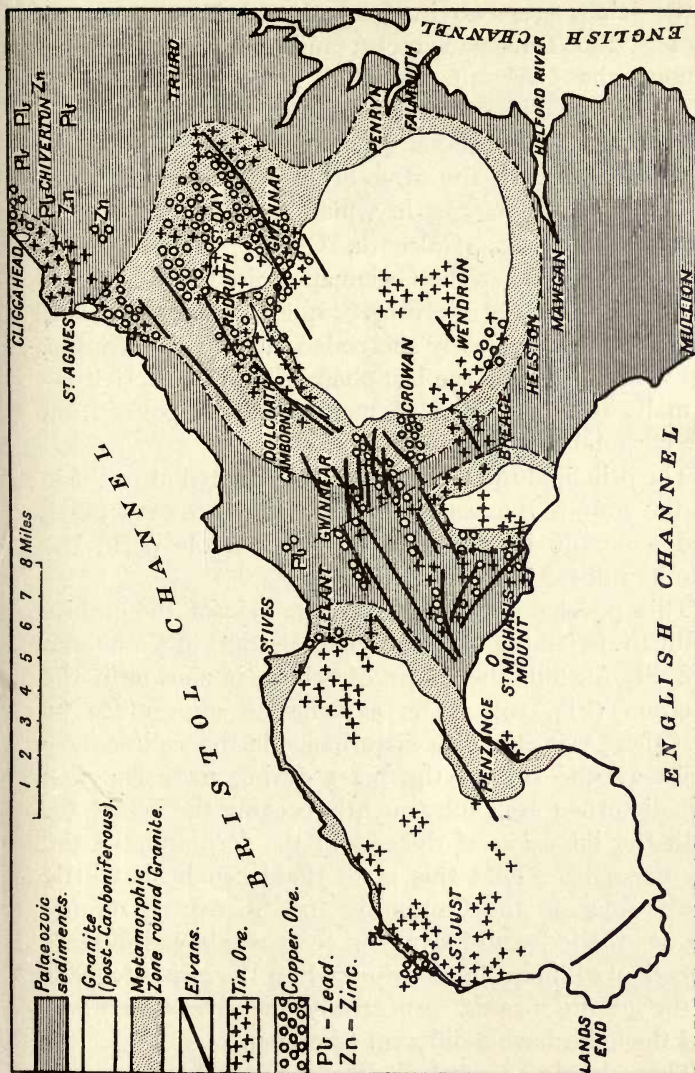
FIG. 18.—GEOLOGICAL MAP OF WEST CORNWALL, SHOWING THE RELATION OF THE ORES TO THE GRANITE, ELVANS, AND CONTACT-ROCKS.

Ordovician age, two in Central and East Cornwall among the Devonian rocks, and one in Devonshire among the Carboniferous and Devonian sediments. Here and there are smaller granite intrusions, occurring as satellites of the larger masses.

Connected with the same eruptive centres, and particularly in the regions in which the most celebrated mines occur—*e.g.*, Dolcoath, Cook's Kitchen, Carn Brea, Wheal Basset, the Gwennap United Mines, etc.— there are a number of elvans, or quartz porphyry dykes, whose intrusion closely succeeded that of the granite, but which preceded the last phase of eruptive activity— namely, the emanation of metalliferous vapours from the consolidating granite magma.

The principal mineral centres are situated at one side of the granite masses with which they are associated, and generally in the metamorphic aureole or in the granite not far from the periphery.

This peculiar localization at one side of the granite is illustrated in the tin and copper districts of Camborne and St. Austell, the latter of which is shown in the diagram (Fig. 19). The explanation appears to be that there was excessive disturbance in the sedimentary rocks at one side of the mass during intrusion, and this disturbed area subsequently became the centre for both the intrusion of dykes and the formation of the ore deposits. That this is so there can be but little doubt since, in the Camborne and St. Austell mining regions the lodes and elvans in each case have the same direction, while in the interior and on the opposite sides of the granite masses, respectively, the elvans are fewer and the lodes have a different direction.

There is also a marked difference in the structures

of the lodes themselves; for whereas in the principal centres they consist of wide zones of much-fissured
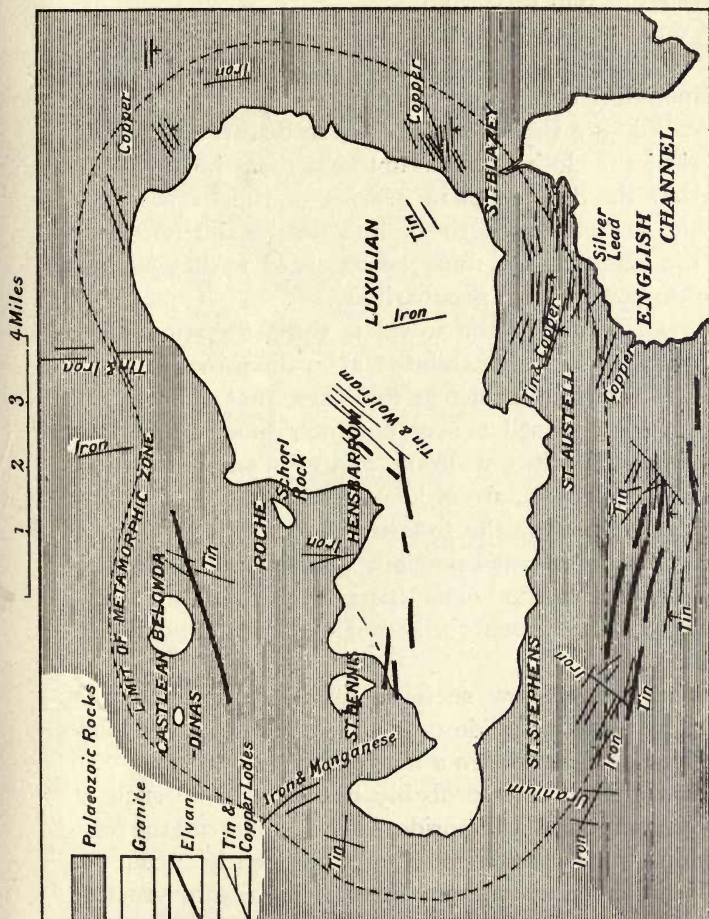

FIG. 19.—GEOLOGICAL MAP OF THE ST. AUSTELL GRANITE, SHOWING THE RELATIONS OF THE DIRECTIONS OF THE PRINCIPAL TIN AND COPPER LODES, IN THE DIFFERENT PARTS OF THE DISTRICT, TO ONE ANOTHER.

rocks, and frequently of shear-zones containing breccias and crushed fragmental material, the lodes in the out-

lying districts consist of clean cracks or joints of remarkable straightness, and, as already remarked, have a different direction.

Consequently, although the veinstones from various parts of either of these mining regions have such well-defined differences in structure, it is probable that the lodes all owe their origin to those disturbances which marked the close of the eruptive activity in the region, so that the differences in bearing of the lodes, as well as the structures of the veinstones in different parts of the same region, must be regarded as having been determined by local peculiarities.

In no region in the world is the association of tin and copper so well exhibited as in the mines of Cornwall, where the evidence indicates that the tin and copper ores, as well as such common mineral associates as arsenical pyrites, wolfram, and even small quantities of zincblende, etc., are of identical age.

Examination of the lode materials, however, shows that the stanniferous portions generally occur in what are obviously the older parts of the veins, and appear to have been formed of the first minerals deposited.

Other cases show such an intimate assemblage of cassiterite and sulphide ores as to render the evidence of successive deposition a matter for doubt.

That the tin was probably deposited from such an active compound as fluoride of tin points to the conclusion that cassiterite would frequently occur as replacements and impregnations of the country-rock in positions inaccessible to other ores, and so always appear to have been the first mineral to be deposited.

Where the sulphides of copper do not occur alongside the cassiterite, they generally occupy a higher horizon in the lode, a peculiarity well exhibited in the Camborne
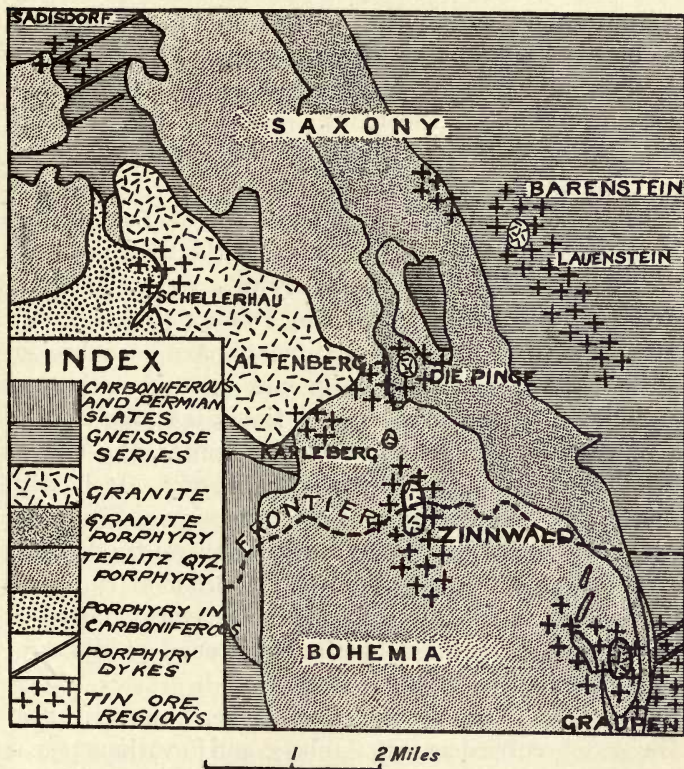

FIG. 20.—THE TIN DISTRICTS IN THE ERZGEBIRGE.
(AFTER K. DALMER.)

mines, where, excepting the outcrops, the lodes in their upper parts yielded copper, and in depth tin ore. This is particularly the case with lodes traversing killas

in the upper part and granite in depth. It may be assumed, therefore, that the temperature of the rocks had much to do with the determination of the horizon at which the ores were deposited.

Tourmaline and chlorite accompany the ores. They occur as alterations of the country-rock, or as slender crystals embedded in quartz, and constitute the well-known ' peach ' of the lodes. Topaz and white mica are also found as products of the alteration in the rocks enclosing the lode.

In the Erzgebirge, on the frontier of Saxony and Bohemia, the zonal distribution of the ores near the granite intrusions with which they are associated is again well exhibited, as was shown by Dalmer (Fig. 20). In that region the Palæozoic sediments have been broken through by successive acid igneous intrusions, the last of which, in post-Carboniferous times, is in the form of a number of granite masses, or laccolites, the largest being that of the Schellerhau in Saxony. It is with this and the smaller bosses of Obergraupen, Zinnwald, Altenberg, and Bärenstein, that the several tin districts are connected. In the Zinnwald a proof of the close connection of the tin veins with the consolidation of the granite is certified by the occurrence of dykes of aplite cutting the veins.

In other parts of the Erzgebirge, however, as at Geyer, Ehrenfriedersdorf, Sauberg, and in various places in the Eibenstock granite-mass near Karlsbad, tin ore has been mined. The other minerals characteristically present are scheelite and wolfram, fluorspar, schorl, arsenical compounds, uranium ores, with occasionally oxide and carbonate of iron, and sulphides of tin, lead and zinc, etc.

Wolfram veins of pneumatolytic origin are associated with the granite of Bergen and Lauterbach, in Bohemia. Near Tirpersdorf the wolfram veins cut both the granite and the altered sedimentary rocks, which, in the contact-zone, have been spotted, converted into andalusite rock, and subsequently tourmalinized.

The wolfram veins are so intimately associated with the tourmalinization of the rocks which they traverse as to suggest a close genetic relationship between the wolfram and boron-bearing minerals, thus constituting a subtype of pneumatolysis. There are not sufficient data to enable the connection of boron and tungsten to be expressed in the form of a chemical equation.

The veins consist for the most part of quartz with drusy cavities into which quartz crystals project. The wolfram occurs among the quartz, and the whole vein has a rough transverse arrangement, as if it had cooled from a state of fusion. A lining of pearl-grey muscovite sometimes exists on the walls between the vein and the country-rock. Pyrites, a little limonite, wolfram ochre, a little manganese ore, and molybdenum, also occur. The rock in the immediate neighbourhood of the vein is tourmalinized.

The general structure of the veins, and the mineral association, is almost identical with that of the Bunny Mine in the kaolinized granite of St. Austell, Cornwall (Fig. 21). In this region, although tourmalinization of the rocks is so characteristic, the wolfram veins are not markedly in intimate association with tourmaline.

In the Cochise mining district (Arizona), L. O. Kellog has described wolfram deposits in quartz veins in connection with granite, but they are of limited occur-

rence. They appear to be more or less connected with the copper ores of the region.

At Long Hill in Connecticut, U.S.A., wolfram, wolfram ochre, and scheelite are associated with fluor-spar, quartz, topaz, and white mica in such meta-
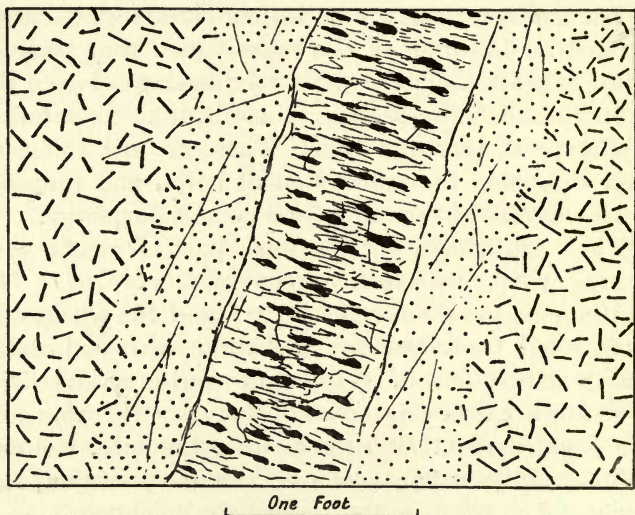

One Foot

FIG. 21.—TIN LODE AT THE BUNNY MINE, ST. AUSTELL, CORNWALL.

The vein infilling is coarse cavernous quartz, having a distant resemblance to comby structure. It is a pegmatite vein, containing tin-ore and wolfram. Some felspar in the vein is kaolinized, while the adjacent granite is altered to greisen. A little fluorspar and tourmaline are present.

morphic rocks as quartz - zoisite - epidote - hornblende rock, occurring at the junction of diorite-gneiss with crystalline limestone. Topaz occurs in particular abundance in a separate lode containing wolfram and other minerals. Some of the wolfram is pseudomorphous

after scheelite. The occurrence of pegmatites with minerals such as fluorspar, topaz, etc., indicates that the wolfram was formed under pneumatolytic conditions from the same magma as that which gave rise to the pegmatites (Fig. 22).

One of the most remarkable deposits of tin ore, from the genetical standpoint, is that occurring at Etta
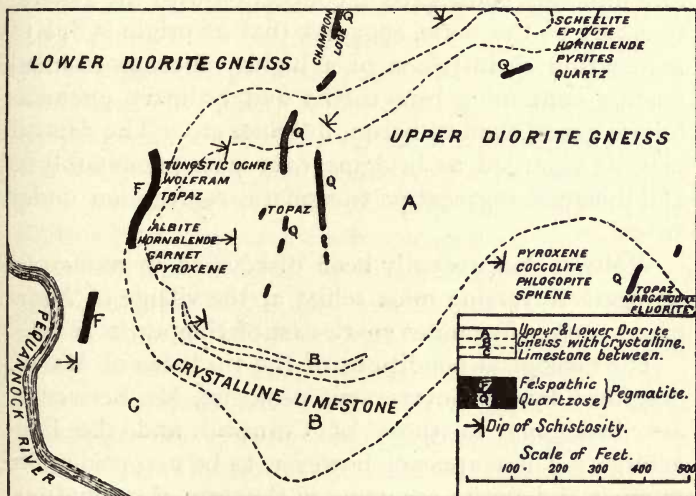

FIG. 22.—GEOLOGICAL STRUCTURE OF THE DISTRICT AT THE TUNGSTEN MINE, NEAR LONG HILL, CONNECTICUT. (AFTER W. H. HOBBS.)

Mine, near Harneys Peak, in the Black Hills of South Dakota. Here there is an exceptional development of pneumatolytic minerals.

Of a roughly oval form, measuring 150 feet by 200 feet, the vein is made up of layers of quartz and felspar, with stanniferous albite and mica ; then crystals of spodumene of enormous size, varying from 10 to 50 feet

7

in length, surrounded by interstitial albite and tinstone. Between this and the country rock is a complex aggregate of muscovite and biotite; tourmaline; apatite, triphylite, autunite, and other phosphates; columbite one crystal of which weighed a ton; tantalite and other rare minerals, together with gold and silver; lead, arsenic, and other sulphides. The large number of rare minerals, considered in connection with the general structure of the mass, suggests that its origin is due to segregation or intrusion of a highly siliceous residual magma containing rare earths and ordinary pneumatolytic gases, such as boron, fluorine, etc. The deposit may be regarded as bridging over pure pneumatolysis and dynamic segregation (magmatic segregation under stress).

Wolfram has recently been discovered in numerous stringers traversing mica schist at the village of Agargaon, twenty-five miles south-east of Nagpur in India.

The geological conditions of the tin lodes of Malay, described by the Government geologist, Mr. Scrivenor, are analogous to those of Cornwall and the Erzgebirge. There appears, however, to be a considerable number of deposits occurring in the form of pegmatites, which have been exploited both by ordinary mining methods (as at Bundi), and by washing in the manner commonly employed in the extraction of tin from alluvium. In Bolivia and Southern Peru the conditions are somewhat different, as in that region many of the tin ore deposits, found up to an altitude of 18,000 feet, are closely associated with ores of silver, in addition to pyritic minerals; the tin ore is found in masses in the gossan, in the secondarily enriched sulphides of silver, and in the unaltered lode-material in depth.

Although granite occurs in the Bolivian ranges of the Andes, the tin and silver lodes are considered to be genetically connected with trachytic and andesitic intrusions which are later than the granite, the deposits affording an example of an intermediate type between stanniferous and plombiferous veins. Associated with the tin ores (oxide and sulphide of tin; and sulphostannates of lead and copper) and the silver ores are calcite, barytes, quartz, wolfram; sulphides of copper, lead, bismuth, antimony, iron; and various silver-lead ores (with chlorides and bromides); but the minerals tourmaline, topaz, apatite, fluorspar, and the accompanying modifications of the country-rocks, such as greisen and schorl rock, are rarely present, tourmaline being particularly uncommon.

Among the principal Bolivian localities for tin ore are Oruro, La Paz, Potosi, and Chorolque; the tin belt also extends to Moho in Peru. At Punitaqui in Chili many of the tin veins, although occurring in diabase, are, in common with gold ores, derived from hornblende-granite, syenite, quartz-diorite, dacite, etc.

The figure illustrates the mode of occurrence of tin-stone in quartzite (Fig. 23).

In Tasmania (as at Mount Bischoff, one of the largest tin mines in the world), Queensland (Herberton, etc.), New South Wales (Vegetable Creek, etc.), Victoria (Mitta Mitta), and West Australia, the tin ore is derived from Permian granite, and occurs in veins in this rock and in the surrounding Silurian slates, sandstones, and conglomerates. With it occur gold, molybdena, bismuth ores, ores of copper with iron pyrites, mispickel and wolfram, together with topaz, tourmaline, fluorspar, beryl, etc.; the deposits are, as a

rule, principally developed near the margins of the granite masses. The slates are also invaded by quartz porphyry dykes, and all the rocks have been extensively altered. In this alteration the felspar and mica have been replaced by topaz, tourmaline, tinstone, and secondary quartz. Fluorspar, pyrrhotite, mispickel, iron pyrites, and carbonate of iron, also occur as replacements.
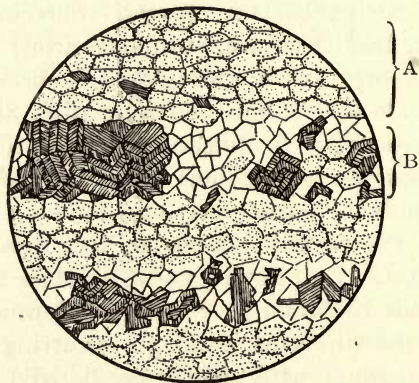

FIG. 23.—DIAGRAM OF MICRO-SLIDE, SHOWING TINSTONE IN BOLIVIAN QUARTZITE. (MAGNIFIED 14 DIAMETERS.)

A, Quartzite: the original grains are enveloped in secondary quartz grown in optic continuity; *B*, tinstone, mica ?, and secondary quartz in bedding-plane.

In the Pretoria district (Transvaal) tin ore has been found in brecciated veins, and as impregnations in granite at Vlaklaagte, twenty-five miles from the capital. Microscopic examination shows that there was mutual interference in the development of the cassiterite crystals and the secondary mica and quartz.

A good account of the occurrence of cassiterite in granite at Zaaiplaats Farm, Waterberg District (South

Africa), has been given by Mr. Kynaston of the Trans-
vaal Geological Survey. The farm is situated partly
on coarse Red Granite and partly on a fine-grained
variety, which is separated from the former by pegma-
tites. The tin deposits occur in a zone a quarter of a
mile in width, extending from Roodepoort to Groen-
fontein. The ore-bodies are commonly in the form of
pipes, about 2 feet in width. The inner portion of the
pipe is an altered granite impregnated with cassiterite.
This is surrounded by a narrow zone of tourmaline-
rock and reddened granite, beyond which comes the
ordinary granite of the country-rock. The tin also
occurs in coarse quartz veins along the junction of the
red and fine-grained granite. Sericite, fluorspar, chlorite,
and occasionally calcite, with mispickel, copper pyrites
and iron pyrites are associated minerals. Wolfram is
recorded from Groenvlei.

In Spain, however, near Malpartida de Caceres
(Estremadura) and other places, the stanniferous lodes
in granite are characterized by an unusually large pro-
portion of apatite, sometimes accompanied by quartz,
calcium carbonate, iron and manganese hydroxide, iron
and copper pyrites, mispickel, copper carbonate, galena
and uranium phosphate. The walls are kaolinized.
The apatite occurs in such quantity as to make it a
profitable product of the mines. The Costanaza vein
is at least two and a half miles long, and where worked
is from 10 to 20 feet in width. It will be seen later that
this type of vein may be regarded as transitional be-
tween normal tin veins on the one hand and apatite
veins on the other.

The occurrence of ores in pegmatites appears to be
more intimately connected with the true differentiation

of igneous rocks than with after-eruptive actions, so that such occurrences are referred to under segregations. In many cases, however, particularly where the pegmatite or giant granite is rotted or altered, the tin ore is of subsequent origin.

In the limestone of Lower Liassic age near Campiglia Marittima in Tuscany, veins of tinstone are associated with quantities of brown hæmatite, which occurs in veins, and also as metasomatic replacements of the country-rock.

Whether there is any actual genetic association of the veins of tinstone with the brown and red hæmatite of metasomatic origin or not, it is certain that the tinstone was derived from the Tertiary acid eruptives of the region. Much of the iron ore with which the tinstone is associated is a secondary product from pyritic ores. There is a total absence of minerals containing lithium, tungsten, bismuth, molybdenum, fluorine, and boron; but there is a little copper ore, principally as malachite. At a distance of about two and a half kilometres north-east of Campiglia a tourmaline-bearing granite of post-Jurassic age, or possibly of post-Eocene age, occurs, and it is probable that the ores are extraction products of this mass.

Among the tin and wolfram occurrences of Dakota, there is one which is comparable to that of tin in limestone near Campiglia—viz., the association of wolfram and scheelite with beds of impure dolomite, grading into quartzite, of Cambrian age. This same dolomite which has been largely silicified and impregnated with pyritic gold ore, constituting the so-called ' refractory siliceous ore ' of that region. The wolfram occurs in flat, horizontal, but somewhat irregular masses, up to 2 feet in

thickness, lying on the basal quartzite or conglomerate. While these ores are of pneumatolytic origin, they also show affinities with metasomatic deposits.

In Perak (in the localities of Changkat Pari, Ayer Dansang, Siak, Jehosophat's Valley, and Lahat) tin ore is found in limestone. In all these cases calcite occurs as a lode constituent, and can be readily distinguished from the crystalline limestone of the country-rock. Although tourmaline, fluorspar, quartz, and other minerals, are not always found associated with the tin, they may occur, together with copper, iron, and arsenical pyrites, bornite, chalybite, ilmenite, etc., in veins in the limestone.

At Winslow in Maine tin ore occurs in veins in limestone, accompanied by fluorspar, mica, quartz, and mispickel.

Tin veins in Silurian limestone occur in the York region, Alaska, associated with an aplite or porphyry dyke, the felspar of which has been partly replaced by fluorspar; lithia-mica, calcite, quartz, and kaolin are also important secondary minerals. The limestones on the north of the dyke contain strings of tin ore, but the other minerals reported from this locality are wolfram, topaz, tourmaline, pyrites, and garnet, with some galena, and a little gold.

Some of the tin produced in the province of Yunnan (China) is said to occur in veins in Triassic limestone.

In the province of Yunnan cassiterite is found in red clay, filling fissures in limestone and other rocks. The ore is accompanied by sulphides in depth. The lodes appear to be connected with tourmaline-bearing pegmatites traversing Triassic rocks.

The occurrence of cassiterite in extrusive rocks is quite exceptional. At Durango, Sombrerete, and other

places in Mexico, granites rising through schists are flanked by rhyolite, rhyolite tuff, and obsidians of late-Tertiary age. The cassiterite occurs both in the granite and in the rhyolite. In the latter it is found as aggregates along parting-planes and faults in the rhyolitic tuffs, in association with magnetite, hæmatite, quartz, fluorspar, topaz and kaolin, hæmatite and chalcedony; in some districts with wolfram, as well as ores of lead, molybdenum, etc. It is quite certain that the metalliferous minerals of the rhyolites were derived from the magma that gave rise to the rhyolite itself, but the conditions of their emanation, and the pressure at which the reactions took place were quite exceptional. In Malacca a stanniferous siliceous sinter contains 0·5 per cent. of SnO_2. In the province of Satsuma in Japan, tin ore occurs in quartzose veins, traversing soft tuffs and Mesozoic sandstones, and shales with, here and there, quartzite bands. Rhyolitic rocks are developed in the region. The tin ore is accompanied by galena, pyrites, and zincblende, of secondary origin.

Of the rarer metalliferous and alkaline-earth minerals, it is of particular significance that while some of the deposits appear to be of pneumatolytic origin, they are allied to the dynamic segregations already referred to. In particular may be mentioned the occurrence of minerals containing fluorine, chlorine, boron, zirconium, thorium, and tin, in pegmatites differentiated from the augite and nepheline syenites of the igneous complex of South Norway; in Eastern Lapland (Kola Peninsula); near the bay of Kangerdluarsuak in Greenland; in Brazil, etc. These, like the pegmatites of Etta Mine, appear to bridge over the purely pneumatolytic with the segregated types, and the minerals, such as

lavenite, eucolite, sodalite, melanocerite, tourmaline, datolite, nordenskioldite, and zircon, bear the same relation to the nepheline and augite-syenite that the pegmatites containing topaz, beryl, and tinstone, do to granite.

In Greenland, tin ore, wolframite, sulphides of lead, zinc, and copper, with mispickel, are accompanied by rich deposits of fluorine-bearing minerals in connection with granite masses. Cryolite, fluorspar, quartz, microcline, hydrated mica, carbonate of iron, and columbite, are the principal vein associates; while such minerals as topaz, tourmaline, and phosphates are absent.

Copper Sulphides.—Sulphide ores, unaccompanied by cassiterite, have in some districts been regarded as originating closely after the intrusion of the igneous rocks from which they were derived, and to have been formed under conditions of pneumatolysis. The very varied conditions under which sulphidic ores may be concentrated, owing to their solubility and wide occurrence in igneous rocks, renders a classification of the processes connected with the formations of pyritic nature a matter of difficulty.

The copper lodes of Cornwall and their association with tin and tourmaline have already been referred to (p. 84) as 'cassiterite veins characterized by presence of copper,' but it would be equally correct to speak of them as 'copper veins characterized by the presence of cassiterite.'

There are, however, elsewhere copper lodes of pneumatolytic origin, in which tin ore does not occur. In Norway copper veins associated with greisen were derived during the consolidation of acid plutonic rocks.

Subordinate occurrences also exist in the Southern

Tyrol, where copper sulphide is found in veins, in augite andesite, containing in addition iron pyrites, tourmaline, scheelite, apatite, felspar, and quartz, in such intimate association as to indicate contemporaneous formation.

Tourmaline - copper veins also occur in Oregon, Mexico, and German South-West Africa. Copper veins characterized by tourmaline-rock and greisen are well represented in Telemarken in Southern Norway, where they exist as bodies of various forms, in the gneisses, schists, and granites. The other ores are pyrrhotite, iron pyrites, molybdena, hæmatite, sulphides of arsenic, zinc, lead, bismuth, etc.; fahlerz, uranium ores, magnetite, with titanite, etc., also native gold and silver, in association with quartz, muscovite, calcspar and dolomite, fluorspar, tourmaline, and occasionally beryl and apatite.

In this locality Vogt studied the mineralogical changes which took place in the country rock enclosing the veins. The granite consists of quartz, microcline, orthoclase, oligoclase, and a little magnesia mica, with accessory titanite, zircon magnetite, and apatite. There is practically no muscovite except where the rock has been altered, and there it consists mainly of muscovite and quartz, with unaltered accessory minerals and a little fluorspar and epidote.

In New England the copper deposits of Vermont, South Strafford, and other places, are connected with granite. At Vermont the country-rock consists of schists with calcareous bands, intruded by granite and pegmatite in which copper and iron pyrites are found with tourmaline. At Ely (near Copperfield) and the Elizabeth Mine (South Strafford) the ores are similar,

and occur in saddle-shaped bodies along folds in the schists, or in long chimneys at the contact of granite veins with mica schist. All these deposits have been formed under pneumatolytic conditions.

In the State of Oregon copper and iron pyrites occur in association with quartz and tourmaline in fissures, and as irregular deposits.

The association of tourmaline with quartz, copper and iron pyrites, mispickel, blende, and carbonate of iron, in a fissure varying from 1 foot to 18 feet in width, and traversing the granite, is known in the Foss River district, Washington State.

The important Chilian copper deposits are associated with andesites, porphyries, diorites, and gabbros of various ages with a little granite or syenite, and appear to be of pneumatolytic origin. In the upper parts of the veins, however, the copper ores are oxidized to carbonates, oxides, etc., with which native copper also occurs. Below these come the original sulphides, mixed with tourmaline, quartz, chlorite, and micaceous minerals ; a little gold is also present.

At Copiapo the veins contain in places molybdenum glance with copper sulphide and tourmaline.

In the province of Atacama secondary copper ores occur with tourmaline.

Gold.—In Thelemarken gold exists in the copper-tourmaline veins, connected with intrusions of quartz-mica-diorite. The veins are siliceous, containing in addition tourmaline, carbonate of iron, and muscovite or epidote. The ores are gold, copper and iron pyrites, and sulphides of lead and bismuth. It should be observed that the gold occurs principally in the quartz in intimate association with bismuth, while tourmaline

is found near the walls of the veins, which are altered to quartz and muscovite. The carbonate appears to have been the last of the minerals to arrive in the lode-fissures.

Some cassiterite veins contain gold associated with mispickel, as at Villedor, in the North of France; while the cassiterite-tourmaline veins of Cornwall, and of Eibenstock in the Erzgebirge, are slightly auriferous.

The pneumatolytic origin of some gold veins is again proved by the occurrence of the metal with wolfram and other minerals. It is found associated with wolfram in Colorado, and with scheelite and sulphides of iron, copper, and arsenic, in Idaho; with scheelite, quartz, sulphides of iron, lead, and zinc, and carbonates of lime and magnesia, at the Val Toppa Mine, Piedmont; in wolfram and scheelite at Otago (New Zealand), connected with granite. The veins are of the true cassiterite type, but are characterized by an unusual amount of gold.

In Brazil, near Ouro Preto, an excessively siliceous vein occurs between a hanging-wall of hornblende schists (some of which are hæmatitic, and when decomposed produce itabirite) and a footwall of mica-schist and quartzite containing graphite, staurolite, garnet, etc.

The gold is found principally in the vein, with tourmaline and sulphide of arsenic and iron, but also in the quartz. A bismuth and gold alloy occurs here.

A younger generation of gold occurs with calcite. Sulphides exist in small quantity, while fine-grained tourmaline, felspar, biotite, etc., are found as nests and streaks in the vein-quartz and in the country-rock.

The biotite-copper veins of Rossland (British Columbia), described by Lindgren, appear to be of pneu-

matolytic origin. The deposits yield both gold and silver values, particularly near the surface. The ores occur either in single, or compound reticulated, fissures, in shear zones, or as irregular impregnations in hornblendic intrusive rocks.

The ores consist of auriferous pyrrhotite and mispickel, replacing the walls of fissures which are now composed largely of biotite, with hornblende, chlorite, muscovite, calcite, quartz, and garnet. The breakdown of the hornblende and felspar of the country-rock results in its replacement by biotite and pyrrhotite.

Titaniferous Iron Ore, Molybdenite, etc.—According to Hussak, the origin of the gold deposits of Passagem, in the province of Minas Geraes, near Ouro Preto (Brazil), is as follows: The vein is an ultra-siliceous apophysis of a granite, and has been intruded along a series of schists, which it has thermally metamorphosed. The intrusive nature of the vein is said to be indicated by the presence in it of albite, zircon, monazite, xenotime, etc. But although this view has been combated, the gold and associated metalliferous minerals (auriferous mispickel, pyrites, etc., with quartz and tourmaline) may, at all events, be regarded as of pneumatolytic origin.

Of special interest is the occurrence of titaniferous iron oxide in veins in the Grossvenediger granite, and also in the granitic rocks of the Aarmassif (Central Switzerland), where, although of no economic importance as ores, they are of significance as constituting a type of vein intermediate between tin veins of granite and titaniferous masses in gabbro. Although titaniferous minerals are not very prevalent in tin lodes, there are some places, as at Ehrenfriedersdorf, in the

Western Erzgebirge, where titanium is associated with the normal constituents. The above localities, however, are remarkable for containing it in unusual amount. It generally occurs as rutile, occasionally as anatase and brookite and in titaniferous iron ores, in paragenetic association with quartz, fluorspar, calcite, apatite (fluor-bearing), tourmaline, chlorite, muscovite (with and without fluorine), albite, and rarely beryl and molybdena. The alteration of the granite in the neighbourhood of the veins is as follows : Biotite has disappeared, and in the cavities so left an addition of secondary quartz and felspar (albite) has taken place on that of the rock.

According to Weinschenk, the muscovite of the granite near the contact with the slates is replaced by chlorite, while in the schists and slates beyond zeolites occur at a moderate distance from the contact ; but near the contact the place of the zeolites, including prehnite, is taken by augite, epidote, asbestos, and occasionally garnet. Along with these occur magnetite, hæmatite, titaniferous iron ore, and scheelite. Other veins in the district of the source of the River Aar occasionally contain molybdena, leadhillite and other plombiferous minerals, and bornite in association with the sulphides and minerals already mentioned. From the occurrence of small quantities of carbonates of the metals in the Swiss localities, it appears probable that there was a sequence of deposition, and that the carbonates were formed at the close of the true pneumatolytic phase.

The general mode of occurrence of molybdenum minerals suggests their pneumatolytic origin. The principal ore, molybdenite, is commonly found in quartz veins or as impregnations in pegmatites derived from

granites. In Washington State molybdenite is found in considerable quantities in quartz veins traversing granite, while in the State of Maine it is found impregnating both granite and pegmatite.

Among the Canadian occurrences of molybdenite may be mentioned that in which the mineral is found in association with pyroxene, quartz, calcite, pyrites, etc., in veins traversing limestone near granite, so that the origin of the veins may be partly referred to the processes of contact metamorphism.

ORES OF PNEUMATOLYTIC ORIGIN CONNECTED WITH GABBROS AND ALLIED ROCKS.

Pneumatolysis in connection with the basic igneous rocks is as marked, but not so universal a feature as it is in granites. The distinctive characters of deposits given rise to by this type of pneumatolytic action are as follows: firstly, the connection with basic intrusions; secondly, the characteristic type of alteration in the country-rock; and, thirdly, the dominating presence of certain minerals occurring only in subordinate amounts in connection with granite.

With the exception, too, of the somewhat different conditions under which the ores are extracted and secreted owing to the chemico-physical factors governing the consolidation of basic rocks, the general process of pneumatolysis is the same as in granite; and as some of the minerals secreted are similar to important accessory minerals of the basic intrusion itself, the relationship is obvious. To a certain extent the classification of ore deposits is arbitrary, since the principal heads of all schemes are selected according to the importance of the various minerals to mankind, and—

as, for instance, in some gold veins—deposits may be designated by the name of a metal or mineral which occurs in them in quite subordinate amounts.

But a well-marked type of deposit is exemplified by the occurrence of titaniferous minerals and apatite with gabbro, which in Scandinavia (on the west of Christiania Fjord) has been well described by Brögger and Vogt, and in Canada by Sterry Hunt and others.

The gabbros giving rise to these veins are olivine-norite (or olivine-hyperite) and olivine-gabbro, which form two great groups, in which the olivine and hypersthene appear to be interchangeable. This family of rocks is somewhat inconstant as regards its structure and composition, and while different names have been given to the various deviations from the general type, the rock as a whole may be described as a holocrystalline plutonic intrusive mass consisting of augite or other pyroxene and a lime-soda-felspar. The constituent minerals are felspars, ranging from labradorite to anorthite; augite, with accessory bronzite and hypersthene; hornblende and brown biotite as rare accessories; olivine; quartz occasionally; and ilmenite, magnetite and apatite as accessories.

The principal agent in the extraction of titanium and most of the metalliferous minerals of the lodes is chlorine, which plays the same part in the gabbro magma that fluorine does in granite, so that titanium is probably extracted as a chloride, and deposited, according to the equation

$$TiCl_4 + 2H_2O = TiO_2 + 4HCl;$$
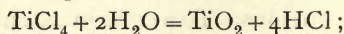
and similarly iron,

$$Fe_2Cl_6 + 3H_2O = Fe_2O_3 + 6HCl,$$
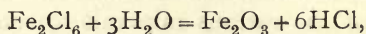
and other minerals form soluble compounds which, in the presence of steam, are capable of extraction and secretion. In addition to these, however, Vogt believes that the phosphorus of the abundant phosphates in the veins was extracted according to the equation

$$PCl_5 + 4H_2O = 5HCl + H_3PO_4.$$
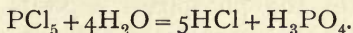
The phosphorus of the magma uniting with chlorine is extracted, and in presence of steam is decomposed and carried away as phosphoric acid. Fluorine and boron are seldom present in the basic rocks.

In addition to elements extracted as chlorides, there are some metals which were possibly extracted at an early stage as sulphides, or were extracted as chlorides, and, subsequently reacting with sulphuretted hydrogen, changed to sulphides—*e.g.*,

$$PbCl_2 + H_2S = PbS + 2HCl.$$
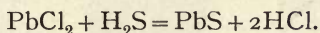
Carbon dioxide was probably evolved at a late stage.

The minerals of the titanium-apatite veins are as follows: Chlor-apatite, wagnerite (Mg_2FlPO_4), titanite, rutile, titaniferous iron, specular hæmatite, magnetite, anatase, pyrrhotite, iron and copper pyrites, lead sulphide, magnesia-mica, enstatite, augite, actinolite, asbestos, scapolite, orthoclase, albite, oligoclase, quartz, tourmaline, epidote, prehnite, talc, chlorite, and calcite. Fluorspar does not occur.

The gabbro in the neighbourhood of the veins is changed to scapolite-rock. The hydrochloric acid of the fissures, together with sodium and calcium chloride, reacting upon labradorite, with the small addition of chlorine up to 3 per cent., and of lime, results in the formation of scapolite. This commences along twinning-

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planes and cracks, and at the margins of the crystals. The diallage goes to hornblende, while iron ore is partly dissolved, and there is also the formation of enstatite, magnesia-mica, and rutile.

In Southern Norway two types of gabbro are represented, and in the phosphate deposits of the Laurentian and Cambrian rocks of Ontario the conditions
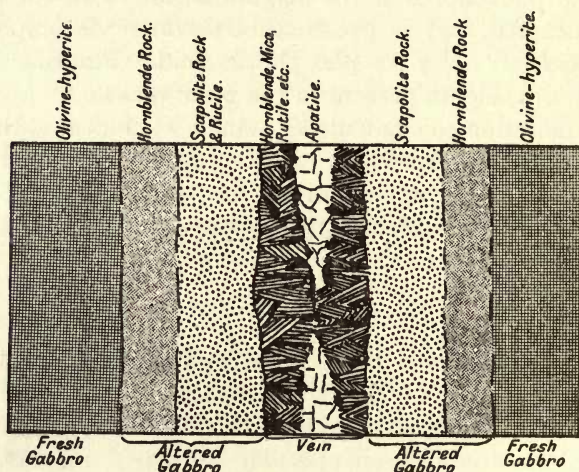

FIG. 24.—TITANIFEROUS APATITE VEIN IN GABBRO.
(AFTER J. H. L. VOGT.)

are similar, with the exception that the gabbro is probably more basic than the Norwegian types. Magnesia is not so abundant, and there is less rutile but more zircon. In addition to this the apatite is fluor-bearing, so that fluorine appears in the Canadian deposits to have replaced the chlorine of the Norwegian. In Canada crystals of apatite weighing 700 pounds have been found. Mica is extracted and sold. Sphene crystals 1 foot

long, and zircons 1 foot in diameter, have been taken from the veins, which can be traced for miles.

It should here be observed that the pneumatolytic processes in granite and gabbro have these points in common. The minerals extracted are practically identical, with the exception that what is abundant and characteristic of granite is only accessory in gabbro, and *vice versa ;* this is also true of halogen-mineralizers and other gases, and also with respect to the soda and potash.

Here and there, however, exceptional transitional types exist which recall both the normal acidic and basic occurrences. The temperature and conditions of intrusion of the gabbros dependent on their lower melting-point, probably affected the general conditions under which the minerals were secreted.

CHAPTER IV

HYDATOGENESIS—DEPOSITS FORMED BY AFTER-ERUPTIVE ACTIONS WHICH ARE NOT PNEUMATOLYTIC

THE lodes formed under conditions less active than those of pneumatolysis, but nevertheless connected with the intrusion of igneous rocks, may be divided into two classes, comprising the sulphidic and the oxidic ores. Of these, by far the larger class is the sulphidic, including as it does many copper, argentiferous lead, zinc, bismuth and antimony, gold, and other ores.

Some of the deposits have close affinities with those of pneumatolytic origin in the nature of the minerals, in their connection with plutonic igneous masses, etc. And others, although described under the separate heading of 'metasomasis' (or 'metasomatism'), are genetically connected with this group. Owing to the fact that many of the minerals in this group are decomposed with comparative ease by underground waters, and under suitable conditions reconstructed, it is sometimes difficult to definitely assign the exact mode of origin to them; but, fortunately, the general circumstances of their occurrence assist in this determination; the question whether these deposits are mainly original or secondary, or whether, as in cases of metasomatism, they are of direct origin or result from the secondary action of ground

waters, is usually readily disposed of. As a general rule, however, the deposits of this class are not confined to the aureole of metamorphism of the igneous rock from which they are derived; and if they happen to occur in the metamorphic zone or in the igneous rock itself, the formation did not take place until the metamorphism was complete and the igneous rock consolidated.

Briefly, hydatogenesis is generally post-pneumatolysis; or if it happens to be contemporaneous, then it must take place beyond the influence of the heated igneous mass and outside its metamorphic aureole. These conditions may be diagrammatically illustrated, as in Fig. 25.

In some deposits of the hydatogenetic class, the conditions of deposition appear to have commenced with pneumatolysis and ended with hydatogenesis. This is obvious where the greater part of the vein material was deposited in the final phases of lode-forming activity; the pneumatolytic phase being indicated by certain alteration-types of the country-rock near the vein, or by pneumatolytic minerals occurring in subordinate amounts. Indeed, in the absence of minerals indicative of the mineralizers characterizing veins of pneumatolytic origin, the lodes may generally be considered to belong to the hydatogenetic class. It should be recollected, of course, that the solutions were at first extremely hot, and minerals deposited from them are said to be of hydrothermal origin. From this point of view the hydrothermal phase of deposition from underground water may be regarded as bridging over the pegmatitic and ordinary hydatogenetic types of ore formation.

There is a third class with which some of these

FIG. 25.—DIAGRAM ILLUSTRATING THE RELATIONS OF THE VARIOUS TYPES OF ORE DEPOSITS DIRECTLY DERIVED FROM IGNEOUS ROCKS.

DISTANCE FROM INTRUSIVE ROCK
Indicating thermal conditions, and consequently the
intensity of contact Metamorphism.

The Pegmatitic, Pneumatolytic & Hydatogenetic
types of deposits are rough measures of the
thermal conditions under which they were
secreted.

Intrusion of Igneous Rock

Intense Heat

Cool Rocks beyond Metamorphic Aureole.

Most Intense.

CONTACT METAMORPHISM.
PERIOD DURING WHICH DEPOSITS ARE FORMED
DIRECTLY FROM IGNEOUS ROCKS.

Feeble.

CONSOLIDATION OF IGNEOUS ROCK

PEGMATITES

PNEUMATOLYTIC DEPOSITS

Cooling of Igneous Rocks

Limit of Contact Metamorphism

HYDATOGENESIS

Metamorphism

Metamorphic Aureole.

Igneous Rock Sedimentary Rocks.

deposits have close affinities, but since they consist of hydatogenetic and other deposits profoundly altered by contact with heated igneous masses, they are treated under the separate chapter dealing with metamorphic deposits, and not in this section.

It will readily be recognized, therefore, that the criteria for the determination of the question as to whether, say, a copper deposit is of pneumatolytic or of hydatogenetic (or hydrothermal) origin are to be found not necessarily in the nature of the metalliferous minerals themselves, but in the nature of the accompanying non-metalliferous minerals, both in the lode and in the walls of the lode, together with a general review of the relations of the deposit to the eruptive rocks from which they were drawn. The conditions of hydatogenesis give ample scope for the formation of an extensive variety of deposits in this group. The deposits may have been deep-seated or comparatively superficial; they may be connected with basic or acid plutonic or volcanic rocks; and the variety of minerals comprised in the group may be extracted and secreted shortly after, or at a considerable period after, the eruption of the rocks. In the segregative hydrothermal and pneumatolytic groups, the contiguity of the deposits to the igneous rocks from which they are sprung is itself almost sufficient to prove the connection, apart from mineralogical considerations; but in the hydatogenetic group the deposits, not being restricted to the immediate neighbourhood of the rocks giving rise to them, cannot with confidence be classified according to the nature of the associated igneous rocks, so that it is customary to classify them according to their dominant metalliferous and other

mineral-associations, with a reference to the parent magma where this can be made. This method is identical in principle with the arrangement proposed by Breithaupt as far back as 1852, and, with the exception that it has undergone revision and amplification, it holds good in its essential particulars to-day.

This mode of classification cannot be said to be strictly genetic, and in itself is liable to fail here and there, owing to the numerous questionable occurrences in which abnormal developments of one type of vein may appear to have closer affinities with some other type.

It must be observed, also, that there is a tendency in ordinary classifications to ignore the economically less important minerals. It is frequently the case with gold, for instance, to designate a deposit as being a gold ore, when it might more accurately have been placed in the category of pyritic ores characterized by the presence of gold or other minerals.

With transitional or mixed types the case is often peculiarly involved, and the genesis a matter for speculation only; as several of the veinstone-accompaniments of the metalliferous minerals are capable of being transported by different carriers or mineralizers in addition to water alone, the alteration of the country-rock does not generally supply the key to the origin of the deposits. Under these circumstances, therefore, the description of ore deposits of hydatogenetic origin under certain heads is somewhat arbitrary, and generally confined to a mere account of apparently independent and transitional types, without special reference to their genetic connection with the igneous rocks.

Sulphidic Veins of Hydatogenetic Origin.

In this group of mineral veins the modern writers recognize certain classes connected by transitional types, in which the distinctions are in some cases quantitative only, and in others are of doubtful value.

PRIMARY GOLD VEINS.

A large class of veins which carry gold in important quantity is found in rocks of all ages, but principally in the older formations in proximity to acid and intermediate intrusive rocks. In particular these veins occur largely in gneisses and schists, being frequently associated with granite and its modifications.

In some cases the gold occurs in what appears to be the ultra-acid modifications of pegmatites, in which the various phases between true quartz veins and true pegmatites are said to be traceable. Such veins are regarded as differentiation products of igneous magmas.

Other igneous rocks which may give rise to gold veins appear to comprise practically the whole series of acid and basic intrusive and extrusive rocks, but among those to be particularly mentioned are granite, diorite, augite-syenite, and other allied plutonics; dykes of porphyry and lamprophyre; and among the lavas andesite, trachyte, and rhyolite.

Gold has a wide distribution, occurring in appreciable or minute quantities in most if not all sulphides; it is generally found in silver compounds, and with the rarer metals rhodium, palladium, etc. It is known to occur widely in the form of compounds with silver and tellurium.

It is commonly present in iron pyrites, and in workable quantities is frequently associated with other sulphides, such as those of zinc, lead, antimony, and copper.

It is also frequently accompanied by zincblende, galena, antimonite, and mispickel, and occasionally by compounds of manganese, molybdenum, bismuth, tungsten, and other metals.

In California (San Andreas) uranium ochre has been found characterizing some deposits of gold; while in Arizona (Yavapai and Yuma) vanadates of lead are distinguishing features of argentiferous gold ores. In Nevada and Arizona molybdate of lead in association with vanadates occurs in the Comstock and other gold mines.

It has been remarked that the gold obtained from lodes in the Palæozoic rocks of the Transvaal, Australia, New Zealand, California, and other parts of the world, is high-grade, while that derived from lodes connected with the latter eruptive rocks, such as andesite, is alloyed with a considerable proportion of silver. Möricke recognizes three types of lodes: (1) Those connected with syenites, granites, and gneisses, as in Bohemia; (2) those with trachyte and andesite; and (3) those connected with basic eruptives containing, instead of quartz, such minerals as calcite and barytes, and characterized by high percentage of silver. A fourth class may be added where, as in Queensland and the Urals, gold is found in serpentinous rocks.

The principal non-metalliferous vein-material is quartz, which may occur alone or with carbonates of lime, iron, manganese, etc. Barytes and fluorspar are sometimes distinguishing features, while tourmaline,

orthoclase, and other silicates, may be significant vein-constituents.

In what form the gold was extracted and transported to positions in which it is found in veins of hydato-genetic origin is uncertain. The solution of gold in the magma from which it came, and its deposition in the fissures in which it is found, is closely connected with that of the sulphides with which it is associated; and it is probable that the conditions controlling the deposition of the gold and sulphides are similar.

The solubility of gold in alkaline sulphides, chlorides, iodides, silicates and carbonates, and other solutions in the form of free gold, chlorides, tellurides, etc., is a well-known chemical fact the bearing of which in its connection with the formation of gold ores is empha-sized by the presence of associated minerals corre-sponding to chemical reactions supposed to have taken place. In all probability gold-solutions were very dilute, and contained other dissolved solids, and gases. The precipitation of the gold from the solutions was effected mainly during the precipitation of the sulphides which accompany it, but to what extent mass action or purely chemical action have played their parts is an unknown factor. The presence of organic matter in the walls of lodes—graphite, hydrocarbons, etc.—or of sulphides, has certainly accounted for local enrichment in many cases, while in some examples, where the gold ores are principally secondary concentrations near the surface, ferrous sulphate has been the precipitant. Changes in the alkalinity or acidity of the solutions, produced through the action of free acids or alkalis on materials in the lodes or country-rock, account,

no doubt, for the precipitation of many sulphides and gold.

The original solutions which deposited pyritic gold ores contained, in addition to the dissolved sulphides, tellurides, carbon dioxide and sulphuretted hydrogen, together with compounds of silica, lime, iron, manganese, etc.

The presence of quartz and of iron pyrites in gold veins characterizes an important group. In addition there may be present sulphides of copper, zinc, and lead, sometimes occurring in such important amounts as to make it more proper to describe them as auriferous, copper, zinc, or lead lodes, as, indeed, they are so called when the gold is not the most valuable part of the lode.

Compounds of arsenic are also frequent associates of gold.

Pyrrhotite, molybdena, bismusthine, and tellurides are present in many gold-quartz veins. In the typical gold-quartz veins, carbonates are present only in small amounts, and generally as alteration products of the country-rock. Barytes and fluorspar are also rare, but in some districts the gold-quartz is accompanied by tourmaline, felspar, and white mica, indicating close affinities with ores of pneumatolytic origin. These gold-quartz veins when containing silver in appreciable quantities fall into the group of gold-silver veins, in which the silver is one of the principal workable products. As a group, however, the essential components are quartz, iron pyrites, and gold.

The next important subgroup is that containing copper in considerable quantity, and so may be desig-

nated cupriferous gold-quartz veins. Silver is present only in subordinate amounts, but tourmaline and bismuth sulphide are typical accompaniments. Like most other groups of gold veins, this is not very definite, as it has affinities with the tourmaline-copper-gold group, the bismuth-gold group, and other subtypes. In some places the country-rock is greisenized. Pyrites, galena, fahlerz, zincblende with arsenical, manganiferous and other compounds, also occur in subordinate amounts. The veinstones consist mainly of quartz, accompanied by small quantities of tourmaline and calcite.

Auriferous arsenical pyrites characterizes another subgroup allied to the pyritic gold-quartz veins. In addition to mispickel and quartz, there are sulphides of copper, iron, lead, and zinc, in small quantities.

Subgroups, in which sulphide of antimony on the one hand, and of bismuth on the other, are characteristic constituents are recognized in some parts of the world, but the distinction is somewhat arbitrary.

In the antimonial gold ore the gold occurs mainly in pyrites, but also occurs as free gold in quartz. In the case of bismuth-gold-quartz veinstone, its specification of a subgroup is scarcely warranted, as it has close relationship with tourmaline - gold - copper veins, tin ores, etc. In particular, bismuth sulphide and telluride is associated with gold quartz rich in copper.

An association of gold with a particular type of alteration, first noted by J. H. L. Vogt of Christiania, has recently been described by F. L. Ransome. In Nevada the gold ores occur partly in Tertiary rhyolites, andesites, and other lavas, which for the most part

overlie Palæozoic sediments and granite. The characteristic alterations of the intrusions of dacite are of three types, indicating that the auriferous solutions consisted of acid and sulphidic compounds with carbon dioxide. There is no direct evidence of carbon dioxide having been present, but its presence is inferred. The three types are : (1) Silicification ; (2) alteration to soft rock consisting of quartz, kaolin, alunite, and pyrites; (3) alteration to propylite, in which the rock consists of quartz, calcite, epidote, and chlorite, with pyrites, but no alunite. In some of these changes it is seen that the iron from magnetite and ferromagnesian silicates has given rise to pyrites, while alunite and kaolin have been formed from the potash and alumina.

The foregoing types, as a whole, constitute a class in which the gold occurs with pyrites or as native gold in quartz associated with special minerals distinguishing the subgroups.

The type described below has features which contrast it with the foregoing both in the manner of occurrence of the gold-minerals and in their commercial treatment for the extraction of the metal.

The group referred to is that known as the 'gold-telluride group.' In the telluride ores the gold occurs as a definite telluride of gold with silver, lead and antimony; or it may also occur as native gold accompanied by various tellurides. The veinstone is principally quartz and fluorspar, with which there may be some carbonate; while, as at Boulder County (Colorado) and Kalgoorlie, the vanadium-mica, roscoelite, is found in association with tellurides. The telluride ores in-

variably occur in small veins in comparatively young hypabyssal rocks, a fact which distinguishes them from the ores of most other classes.

They are related to the telluride gold-quartz group on the one hand, and to the sulphidic gold-silver veins on the other.

A third great group of gold-bearing veins comprises those known as the 'auriferous silver ores.' It is a large but ill-defined and variable group in which the relative amounts of the silver and the gold are very inconstant. It has affinities with the siliceous native-silver ore veins containing gold; but its position in the classification adopted is that of a transitional type between the gold and silver groups as a whole and the sulphidic lead and zinc veins. Quartz is an important constituent, but carbonates, barytes, less commonly fluorspar, and more rarely silicate of manganese and felspar, are distinctive constituents of the lodes. Iron pyrites is also present, and may or may not be auriferous. Zinc, lead and copper sulphides are also generally present in very variable amounts. While arsenic is absent, antimony occurs in various sulphides, and particularly in fahlerz. The auriferous silver ore veins are generally connected with Tertiary eruptive rocks, such as rhyolite, dacite, andesite, and basalt, and also with the altered dacite and andesite called 'propylite.'

The propylitization is not universal in the intermediate lavas, while the veins do not necessarily occur actually in the eruptive rock itself.

Sulphidic Siliceous Gold Veins.—At Barberton, in the South-Eastern Transvaal, a series of chloritic

and quartzose schists, slates and quartzites, known as the 'Swaziland series,' is intruded by granite.   Both of these are traversed by diorite.

The lodes consist of quartz, with free gold, pyrites and, rarely, tellurides.   Other minerals, such as pyrrhotite, arsenic and copper sulphide, and rarely galena and antimony, are also found in small amounts.   At Lydenberg, farther north, the veins belong to the cupriferous gold-quartz group.   They occur in sandstones and in dolomite.   The dolomite contains the most important deposits.   Near the veins the dolomite is silicified, while interbedded greenstone is kaolinized.   The veinstones have been affected by secondary actions which have brought about a secondary enrichment of gold; they consist of friable quartz with cavities containing specks of gold, secondary copper ores, and bismuth compounds.   (See p. 294.)

At Um Rus, in the eastern desert of Egypt, veins of quartz occur in granite.   The granite is intersected by dykes of greenstone and porphyry.   The lodes in ancient times were worked for gold.

In Australia there is a wide distribution of gold in various districts.   In Bendigo and Ballarat the lodes are very numerous, sometimes constituting stockworks. They occur principally in Silurian sediments, and consist of quartz in which gold can often be seen.   Gold also occurs in pyrites and in mispickel, while galena and zincblende are also found.   In the Bendigo region the quartz veins traverse, at right angles, beds in which there are small persistent pyritous and bituminous seams, known to the miners as 'indicators.'   Where the lodes cross the indicators they are generally rich.

The Bendigo district is also noted for its saddle-reefs.

The Silurian sandstones and shales in this district are thrown into a series of sharp anticlinal folds, extending for several miles; at the apices of the folds there are bedded quartz veins in the form of saddles. In some cases there is a succession of as many as ten of these saddles. There are three principal anticlinal axes. The district is traversed by dykes of monchiquite, while a post-Silurian granite occurs in the south of
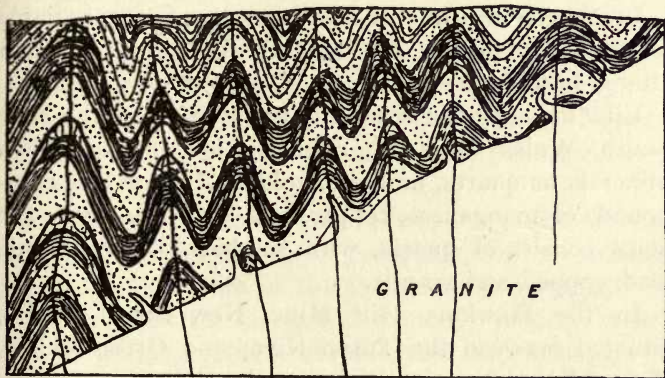

GRANITE

FIG. 26.—STRUCTURAL ARRANGEMENT OF THE SILURIAN SLATES AND SANDSTONES AT BENDIGO, IN WHICH THE AURIFEROUS SADDLE-REEFS ARE FOUND.

the region. Albite is occasionally found in intimate association with the gold-quartz of the saddle reefs, but lime-soda felspars are absent, and in this respect the lodes are genetically connected with the type represented by the Great Mother Lode of California, the quartz veins of Victoria, and the lodes of Douglas Island (Alaska).

In Queensland the Carboniferous sandstones, coal-bearing shales, and conglomerates, with intrusive green-stones, are traversed by quartz veins containing gold

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principally where they occur in the sediments, and more particularly where these are pyritous or carbonaceous. (Hornblende granite is met with, and the allied type known as tonalite.)

At the Mount Morgan Mine the backs of the lodes consist of secondary oxidized minerals. Below, the lode consists of quartz with auriferous pyrites. The pyritic quartz veins occur as a stockwork, in the neighbourhood of which the country-rock is silicified.

In New South Wales the veins are of very variable width, occurring in schists and slates, and also in altered hornblende granite.

Like most pyritic veins, the upper parts of the New South Wales veins are oxidized, and contain such minerals as quartz, limonite, gold, and secondary compounds of manganese, copper, and lead. In depth the veins consist of quartz, with sulphides of iron, zinc, lead, copper, and arsenic.

In the Hawkins Hill Mine, New South Wales, situated between the Turon River and Green Valley, the gold is richest in the lodes where they cross black slates. The hill itself consists of Silurian conglomerates, sandstones, and slates. The lodes are principally quartz, which in places is displaced in favour of muscovite. Calcite, zincblende, galena, and marcasite, are also present as vein-minerals.

The Lucknow district in New South Wales is situated 200 miles from Sydney. There gold occurs in calcite veins in serpentinized basic igneous rock. The deposits occur mainly at the junction of the serpentinized and unaltered rock.

In the Northern Celebes (Malay Archipelago) the gold veins are connected with highly felspathic diorite-

porphyrite, which has been altered to propylite. (Granite also occurs in the region.) The quartz veins vary in size, and contain subordinate amounts of calcite intergrown with the quartz. The sulphides comprise mispickel, pyrrhotite, and pyrites, with small local occurrences of galena, zincblende, and stibnite.

In Woodlark Island, New Guinea, which is composed of volcanic rocks, the gold deposits occur as impregnations of the country-rock in association with pyrites, galena, and calcite. The low-lying coastal districts do not contain workable minerals, since they are covered by coral up to an altitude of 150 feet.

The Californian gold deposits of the Sierra Nevada have been celebrated in the past for their extraordinary richness.

The lodes commonly have the same strike as the upturned sedimentary rocks composing the mountains, and are found either in the sediments or frequently at the junction of the slates with plutonic eruptive rocks, such as granite, gabbro, diabase, and serpentine, all of which are older than the lodes. In particular the veins appear to have a genetic connection with tonalite.

The sedimentary rocks have an easterly dip, and are of various geological ages, from Silurian to Carboniferous (Calaveras Series) and Jurassic (Mariposa Shales).

The lodes consist of quartz, with small quantities of dolomite, calcite, and other carbonates, and occasional barytes. The principal sulphide is iron pyrites, which contains gold. The gold occurs free in the form of leaf, thread-gold, or in large lumps. In Mariposa the gold ores are largely tellurides. Rarely there are zinc, lead, arsenic compounds, and fahlerz, while mercury occurs in some places.

The Great Mother Lode of California in particular is a large belt of veins of post-Jurassic age. It is 114 miles in length, stretching through several counties. In width it varies from a few hundreds to many hundreds of feet, and consists of numberless ramifying veins and brecciated masses. In its neighbourhood the country-rock is extensively silicified and traversed by quartz veins.

FIG. 27.—ALTERED SERPENTINE, IDAHO MINE, GRASS VALLEY, CALIFORNIA. (MAGNIFIED 15 DIAMETERS.) (AFTER W. LINDGREN.)

M, Magnetite; Q, quartz; S, serpentine; P, pyrites.

The quartz is either pure white, banded, or a dark subtransparent variety containing sulphides. The greenish potash mica called 'mariposite' occurs with it. As might be expected in a series of lodes of such extent, there is great variation in the mineral contents of the different parts. In El Dorado, for instance, the porphyrite dykes are traversed by albite veins containing gold. (Compare with the occurrence of gold at Treadwell, Alaska, p. 135). In Nevada the auriferous

pyritic quartz in the granite and diabase is associated with epidote and tourmaline.

At Grass Valley and Nevada City the lodes are connected with tonalite, diorite, diabase, gabbro, and serpentine. The vein material consists of quartz with occasional calcite and potash mica. Opal and chalcedony also occur.

The metalliferous contents, in addition to gold, are sulphides of iron, bismuth, copper, lead, zinc, arsenic,
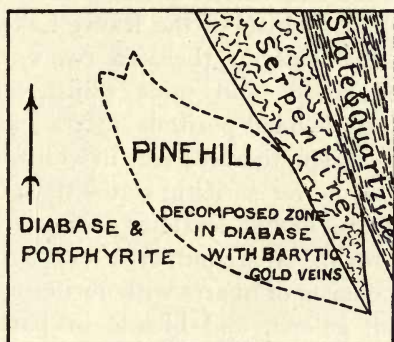
FIG. 28.—PINEHILL GOLD DEPOSITS, CALIFORNIA.
(AFTER W. LINDGREN.)
Scale, 2 inches = 1 mile.

silver, antimony, and mercury. Scheelite is found, and molybdenite is also present.

At Pinehill (California) gold occurs in veins traversing Cretaceous rocks. The minerals appear to favour those positions where the sedimentary rocks are in contact with intrusive rocks, but seldom occur in the diabase and porphyrite. In serpentine and gabbro on the east of Pinehill there are a few veins. Here the gold occurs in association with quartz, sulphides of iron, copper,

lead, and zinc, also with arsenical sulphides, and some-times in combination with tellurides. Dolomite and calcite are occasional accompaniments.

At the top of Pinehill is a mass of diabase porphyrite much kaolinized, and traversed by veins of barytes containing gold. No sulphides are present, but silver is an invariable accompaniment, and occurs separately; the ratio of gold to silver varies from 1 : 1 to 20 : 1. (Chloride of silver is found.) Lindgren believes that the barytes acted as a carrier to the gold.

In the Archæan schists of the Rainy Lake region, on the west of Lake Superior, there are two types of veins. In the older gneiss and mica schist, gold occurs sparingly in interbedded pyritous quartz lenses ranging up to 30 yards in length and 4 feet in width. In similar lenticles in the newer sericitic slates the gold is more abundant. These quartz lenticles enclose fragments of the country rock. A second type of vein occurs in granite, and consists of quartz with auriferous sulphides and free gold, galena, and blende in particular, the granite on each side of the veins having been modified to a sericitic rock.

In Georgia (U.S.A.) auriferous schists and gneisses occur. The lodes proper are in hornblende gneiss, which is altered in some places to a rotten auriferous material known as 'saprolite,' in which are found small quartz veins containing pyrites, galena, copper pyrites, and free gold.

In Nova Scotia auriferous quartz of a peculiar form occurs in metamorphosed shales. The quartz is in the form of barrel-shaped masses, often like a series of logs laid side by side. These masses are really connected together, and it seems that they owe their form

to the contortion and folding of the rocks. Iron pyrites, mispickel, galena, zincblende, and small quantities of argentiferous copper pyrites, are also found.

The veins of the famous Treadwell Mine in Alaska are situated in an intrusion of much-altered and silicified diorite ('soda-syenite'), which cuts across the Carbon-

Three Feet

Gabbro   Albite Diorite   Slate
          traversed by veins of
          Calcite & Quartz
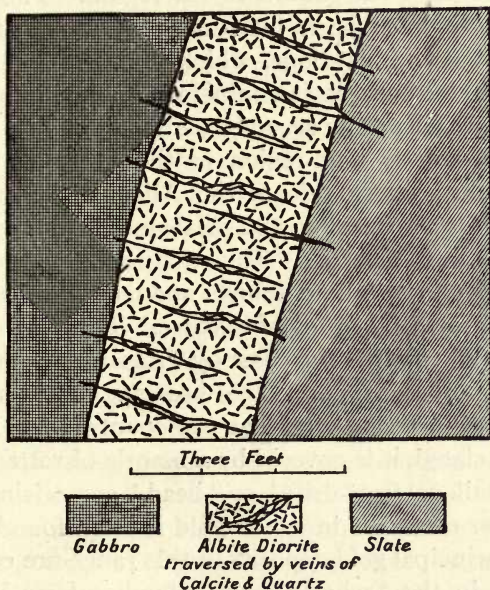
FIG. 29.—GOLD ORE IN TRANSVERSE VEINS IN THE READY BULLION MINE, TREADWELL, ALASKA. (AFTER SPENCER.)

iferous slates of the district. There are younger intrusions of gabbro and basalt, with which the veins are supposed to be genetically connected. The gold occurs in strings of quartz and albite in the diorite, with sulphides of iron, copper, arsenic, and occasionally lead and zinc, molybdenite, realgar, and stibnite;

calcite is also found, but probably it is a decomposition product from the igneous rocks. The veins sometimes cut across the dyke-like intrusions from wall to wall. There is a series of these somewhat brecciated dioritic intrusions in Douglas Island, occurring through a belt of ground three miles long and half a mile wide. No ore is found in the gabbro of the region. The gold is believed to have been introduced by carbonated and mineral-bearing solutions, which attacked the diorite, replacing ferromagnesian minerals by pyrites, and the more basic felspar by secondary albite.

A well-known gold-region in the United States is that of the eastern side of the Alleghany Mountains, between North Carolina and Alabama, including South Carolina and Georgia. The district geologically is made up of crystalline schists and gneiss of Archæan age penetrated by dykes of diabase. These formations are covered towards the coast by Triassic deposits, comprising sandstones and gold-bearing conglomerates; while, owing to the fact that the country here has not been glaciated, it is covered by a mantle of rotted rocks, the so-called 'frost-drift' or 'head,' comprising clays and other materials in which gold is often found.

The principal gold deposits in this range are confined to a belt in the Archæan rocks extending from Virginia to Alabama. The belt reaches a width of seventy miles in North Carolina.

The gold occurs both free and in pyrites; either in interbedded segregation-veins of gold-quartz traversing the metamorphic rocks associated with diabase dykes, or in ordinary veins, cutting slates, gneisses, etc. The pyritous slates show some resemblance to the Norwegian fahlbands.

In addition to this, the gold has been found in the pyrites contained in the diabase dykes, although there are grounds for believing that these intrusives were merely pyritized after intrusion, and assisted in some way in stimulating the lode-forming actions.

In some parts of the gold belt the lodes are accompanied by other sulphides, such as blende and galena; and from the occurrence of tellurium, bismuth, tin ore, molybdenum, wolfram, fluorspar, epidote, etc., in connection with slates and eruptive rocks, it is probable that some of the deposits belong to the pneumatolytic class.

El Callao gold district of Venezuela was once phenomenally rich in gold ores. The lode, from a few feet to 9 feet wide, is situated in a hornblende rock, and consists of pyrites, quartz, and free gold.

Although most of the ores of the desert of Atacama, Chili, are secondarily deposited, reference may be made to the origin of the gold deposits at Guanaco. The gold occurs in numerous cracks, fissures, and shattered masses, in quartz-trachyte which has been much altered. The biotite is changed to viridite and original oxides of iron have been converted to sulphide which contains gold. Near the surface this sulphide has been oxidized, with liberation of free gold, and also formation of atacamite from cupriferous minerals. The deposits are similar in origin to those of Hungary (p. 154).

The district north of Rio de Janeiro (Brazil), near Diamantina and Ouro Preto, is composed of Archæan gneisses and schists, with younger slates, quartzites, itabirite (pp. 108, 352), and sandstones.

The gold veins of hydatogenetic origin here consist of quartz, pyrites, and mispickel. In particular, the veins in the so-called ' jacutinga '—a very friable ferru-

ginous itabirite—are associated with impregnations in the country rock for considerable distances on either side of the actual veins. These have been worked in many cases as open cuts.

Great Britain has been only a small producer of gold compared with the colonial goldfields, but a considerable output has been maintained from mines in Merioneth, such as the Clogau and Vigra mines, and British Gold-Mining Company. The lodes are situated in older Palæozoic rocks (mainly Cambrian), and consist of vertical quartz veins varying from a few inches to 9 feet in width. Granular and coarsely crystalline calcite, which is sometimes auriferous, pyrites, pyrrhotite, sulphides of tellurium and bismuth, are also of common occurrence as vein-minerals.

The gold veins of Saxony, Bohemia, Silesia, and the Tyrol, appear to be connected with granite. The classes of ores and their modes of occurrence vary; the veins are generally quartz containing pyrites, with subordinate and varying amounts of sulphides of copper, lead, zinc, and arsenic. Calcite and carbonate of iron, with barytes, occur in some places, while some deposits are characterized by antimony, and others by scheelite, tourmaline, etc.

The gold veins of Kootenay, British Columbia, are connected with intrusions of diorite or monzonite, and while falling into the group of cupriferous gold-quartz veins, they might possibly be regarded as metasomatic deposits. They were formed after the consolidation of the intrusive rock, but before the intrusion of a series of dykes of lamprophyre (Fig. 30). The conditions were those accompanying dynamic metamorphism, under which head the veins might have been described.

The veins consist of quartz and pyrrhotite, with sulphides of iron, copper, and arsenic. The presence of tourmaline suggests a pneumatolytic origin. There is in addition an abundance of biotite, garnet, hornblende, with quartz, calcite, etc.

The hornblende of the monzonite has been converted to biotite, with liberation of lime. The felspar is also replaced to a certain extent by muscovite, and along
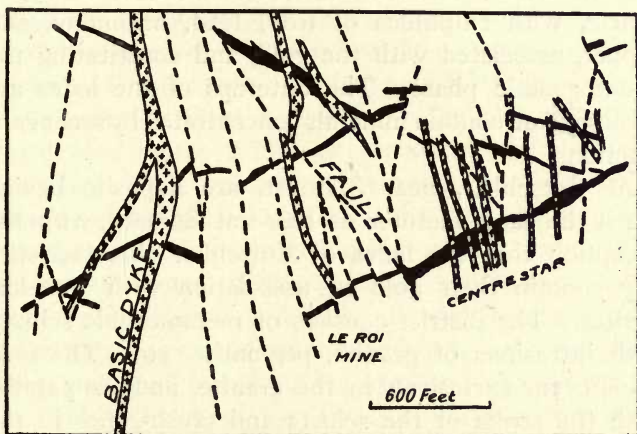
FIG. 30.—MAP OF THE LE ROI MINING DISTRICT, BRITISH COLUMBIA.

cracks and cleavage planes by the sulphide of iron and copper. The final result is that the country-rock is altered to a mixture of quartz, biotite, calcite, and a little secondary felspar.

In the district of Berezov (Urals) there are a number of north and south granite veins in the Palæozoic formations, traversed by east-and-west gold-quartz veins. The granite in the neighbourhood of the veins is altered

to a greisen consisting mainly of quartz and musco-
vite; it is impregnated with pyrites, and is known as
'berezite.' In the adjacent district of Pyzhminskoye
the quartz veins traverse diorite and serpentine in a
similar manner.

The vein materials consist of tourmaline and quartz,
which appear to have been the first of the minerals to
arrive in the veins, and may be ascribed to pneuma-
tolytic action; of calcite and zinc blende; finally, of
quartz, with sulphides of iron, lead, antimony, and
copper, associated with the gold, and constituting the
hydatogenetic phase. The outcrops of the lodes are
oxidized, and contain minerals concentrated by secondary
reactions.

At Kotschkar, near Zlatoust, are deposits having
much the same features as those at Berezov, with the
exception that the lodes of Kotschkar characteristic-
ally contain their gold in association with arsenical
pyrites. The district consists of metamorphic schists,
with intrusions of granite, pegmatite, etc. The gold
veins occur exclusively in the granite, and are parallel
with the strike of the schists and crush-zones in the
granite. The veins contain sulphides of iron, lead,
copper, and antimony, while the granite near them con-
tains such secondary minerals as biotite, chlorite, epidote,
quartz, and carbonates. The lodes have good gossans,
containing iodide, bromide, and chloride of silver.

At Tseliabinsk, 100 miles north of Zlatoust, aurif-
erous quartz occurs in kaolinized masses of rock, with
veins of berezite, in association with sulphides.

Gold with Arsenic.—As an example of the occur-
rence of considerable amounts of arsenic among auri-
ferous sulphides, the Champion Reef in the Dharwar

region in Mysore may be taken. The famous Champion Reef occurs in the Kolar Goldfield, and is worked by the gold mines of Champion Reef, Mysore, Ooregum, Nandidrug, and Balaghat. It has a north and south strike governed by planes of overthrusting in a series of basic lavas, which have been dynamically metamorphosed into hornblende schists. On the eastern margin of these schists is a series of crush-conglomerates derived from granite veins, while on the west is a fringe of schistose and ferruginous sandstones and quartzites, beyond which lies a series of banded granitic gneisses. Parallel with the Champion Reef, and situated about 4,000 feet from it, is the so-called Oriental Reef, which also marks a line of thrusting, and, like the Champion Reef, consists of a number of irregular lenticles of dark bluish quartz, which on the Champion have been mined to over 3,700 feet from surface. The mineral associates of the gold are sulphides of iron, copper, arsenic, zinc, and lead. Pyrrhotite also occurs, and some strings of tourmaline. These reefs occurring along planes of overthrusting are the most ancient of the gold deposits of the district and are intimately connected with its dynamic metamorphism.

A later series of gold-quartz veins in the districts of Kolar, Hutti, and Garag are found traversing the schists transversely, and are associated with dykes of diorite, dolerite, and diabase. They are observed to cut and displace the Champion Reef.

In the province of Ontario, not far from Ottawa, gold-bearing arsenical pyrites occurs in quartz vein-stone, with a little calcite, in connection with syenite.

In the Lake of Woods district, in North-West Ontario, gold is found in fissure-veins in Laurentian rocks and

later granite, also in lenticles of quartz, and in fahl-bands in Archæan schists.   In association with the gold are molybdenite, iron and copper pyrites, bornite, galena, and zincblende, rarely tetrahedrite and mispickel.

Gold with Antimony or Bismuth. — Gold veins characterized by considerable amounts of antimonite, with smaller quantities of other sulphides with arsenic, occur in New South Wales (Arundale) and in the Transvaal (Murchison Range).

The antimonial gold ore group is, however, well typified in Goldkronach, near Bayreuth, in Bavaria, where veins of quartz with auriferous antimonite, native gold and antimony, and sulphides of lead, zinc, and copper, traverse the sericitic Cambrian slates.   In smaller quantities calcite and barytes are found, but also more abundantly carbonate of iron.

On the south of Prague, in Bohemia, there occurs a number of lamprophyre dykes connected with granite.   The antimonial gold-quartz veins of this region traverse both the dykes and the granite.   The metaliferous associates are arsenical minerals and pyrites, with abundant antimonite containing appreciable amounts of gold and silver.   Secondary enrichments of native gold associated with oxidized ores also occur in the gossan.

Near Stavanger, in Kristiansand (Norway), the island of Bömmelö affords examples of gold-quartz veins characterized by the presence of bismuth.

The veins traverse the older diabase dykes and diorite, and also the younger acid dykes of quartz porphyry.

In the schists the gold occurs in lenticular quartz veins, of irregular dimensions, which on the whole

appear to be genetically connected with gneissose granite masses. The lodes also contain sulphides of iron, copper, lead and zinc, and tetradymite (bismuth sulpho-telluride). Native silver also occurs occasionally.

In the southern part of the island the auriferous quartz veins traverse schists, and intrusions of saussuritic gabbro and quartz porphyry. The gold is sometimes found in nests containing calcite and the above-mentioned sulphides. In the veinstone other minerals, such as chlorite, epidote, and felspar, are found.

At Fahlun (Sweden) gold occurs in white quartz associated with older grey quartz and sulphidic copper ores.

In the white quartz the gold occurs native, and is accompanied by compounds containing bismuth, lead, selenium, and sulphur. The connection with the older copper deposits appears to be demonstrated by the presence of sulphide of copper in the newer quartz, which is further characterized by the presence of mica and amphibole

Gold with Tellurium.—The chief localities in which gold is associated with tellurium are Western Australia and Cripple Creek (Colorado), but the peculiarities of other gold-telluride districts are worthy of mention. The two localities mentioned above show similar general characters, for in each granitic rocks are traversed by younger eruptives, with which the tellurides are connected.

In Western Australia the telluride-gold ores occur principally at Kalgoorlie, where, in addition to the hornblende granite of the district, there are serpentinous and chloritic rocks and altered pyroxenites.

The veins occur as fissure-zones varying from a foot to 100 feet in width.

The infillings of the veins consist of quartz with a little calcite and pyrites. The gold occurs native in iron pyrites and as tellurides. There are also frequently sulphides of lead, zinc, bismuth, and even copper; fahlerz and scheelite, and occasionally tourmaline, are found. According to W. Lindgren, metasomatic replacements of the walls of the lodes took place through the action of solutions containing carbonic acid and sulphur, with the development of carbonates of lime, magnesia, and iron, derived from ferromagnesian minerals, and of sulphide of iron from iron oxides. An amphibole-chlorite-zoisite-albite rock has in this way been converted to a quartz-sericite-albite-carbonate rock; gold, mercury, and tellurium were deposited at the same time.

At the outcrops of the veins the tellurides are not found, and they appear to have been decomposed; but in their place is sponge-gold, or a fine yellow deposit of gold known as 'mustard-gold.'

In Colorado the well-known telluride ores of Cripple Creek are connected with volcanic rocks, and dykes intrusive in the granite of the district; the most productive ore is restricted to a circular area, about three miles radius, around Gold Hill.

There is in this district a distinct sequence of eruption, showing changes from acid to basic rocks. The oldest of the intrusives are porphyrites. These were followed by phonolite, which occurs as veins throughout the district, and finally by basic rocks, such as nepheline-basalt, limburgite and tephrite. Volcanic tuffs and breccias with interbedded lavas form the

principal rocks in the neighbourhood of Cripple Creek.

All the rocks are traversed by narrow veins, both simple and composite, in the neighbourhood of which they are often brecciated and extensively altered to kaolin and micaceous minerals, and impregnated with opal and quartz, fluorspar, dolomite, secondary potash-
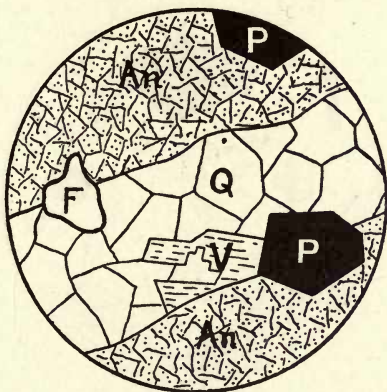
FIG. 31.—SMALL VEIN IN ANDESITIC BRECCIA, INDEPENDENCE MINE, CRIPPLE CREEK, COLORADO. (MAGNIFIED 11 DIAMETERS.) (AFTER W. LINDGREN.)

An, Andesitic breccia ; *P*, pyrites ; *F*, fluorspar ; *Q*, quartz ; *V*, valencianite (orthoclase).

felspar, pyrites, and tellurides (Fig. 31). Of the last, the principal is calaverite, which occurs as a coating on walls of fissures. Molybdenite, argentiferous tetrahedrite, and stibnite, are present.

Other sulphides are uncommon, but zincblende, galena, and chalcopyrite, have been noticed. Roscoelite, rhodochrosite, celestine, and calcite, are seen in the breccia. Molybdenum ores are also met with.

In the granite, the narrow veins are accompanied by considerable alteration on either side, giving rise to replacement - deposits, in which occur chlorite derived from mica, fluorspar, and other minerals. Porphyritic microcline crystals remain unaltered, but the microcline of the ground-mass, oligoclase, quartz, and biotite, have been recrystallized into a porous
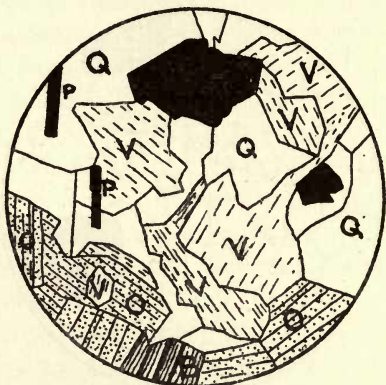
FIG. 32.—'GRANITE ORE,' INDEPENDENCE MINE, CRIPPLE CREEK, COLORADO. (MAGNIFIED 20 DIAMETERS.) (AFTER W. LINDGREN.)

Q, Quartz; V, valencianite (secondary orthoclase); O, original orthoclase; B, biotite converted to valencianite and pyrites; P, pyrites.

mélange of valencianite (secondary orthoclase), quartz, fluorite, pyrite, calaverite or sylvanite, with occasional zincblende and galena. The ' basalt ' dykes are traversed by minute fissures, running parallel to the walls, which ordinarily contain calcite in thin strings.

When the dyke coincides with a zone of fissuring, the fissures contain quartz, fluorspar, and gold telluride (Fig. 33). There is this difference, however, the ores

in the breccias or phonolite are sharply confined to veins, but in the country-rock they occur as impregnations, which also contain pyrite.

In the upper parts of the veins sponge-gold occurs as a residue from the decomposition of calaverite and
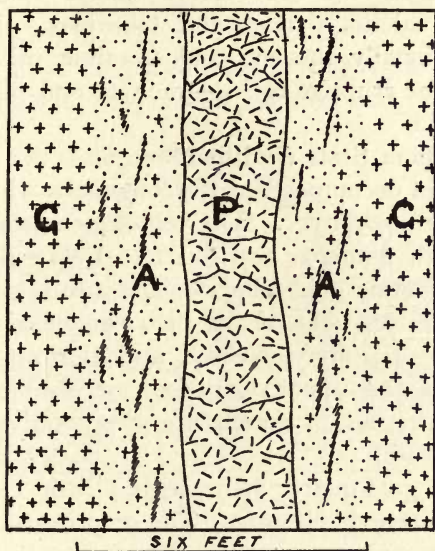
FIG. 33.—GOLD VEIN, CRIPPLE CREEK, COLORADO.
(AFTER T. A. RICKARD.)

G, Granite; P, phonolite; A, altered, impregnated granite, with strings of fluorspar and gold ore.

other minerals. In the Cripple Creek ores there is about 1 ounce of silver to 10 ounces of gold.

Telluride ores are found in other parts of Colorado, as at Boulder, associated with rhyolites and andesites, but there does not appear to be any direct genetic connection between them.

In South Dakota, the ores of the so-called 'siliceous gold-belt' came originally through more or less vertical fissures, from which the much-fractured slates and sandstones were mineralized along a zone over six miles long and four miles wide. The mineral-contents of the impregnations are mainly quartz with a little fluorspar, calcite, pyrites and tellurides. Sylvanite, and occasionally thorium and uranium minerals are found. The eruptive rocks—trachyte and phonolite—are silicified.

In Montana State (Judith Mountains) the gold ores are found in decomposed calcareous rocks which are in contact with porphyry. The vein-materials are mainly pyrites, with fluorspar and quartz. Below the gossan the lodes contain gold-tellurides and a little silver ore.

The eruptive rocks of the district comprise granite and syenite porphyry, syenite, and diorite-porphyrite, with associated minor intrusions of elæolite syenite and tinguaite, all of which are comparatively young in age.

Pyritous gold-quartz veins, with a little copper and tellurium, occur in Nevada. The eruptive rocks of the district are granite porphyry and minette, but there is some doubt as to their connection with the ores, as none of the veins occur in them.

Telluride gold ores are known from Eastern Brazil.

Among the European gold-telluride localities, the well-known veins of the Dacian goldfield in Transylvania, including those of Nagyag, Offenbanya, Verespatak, etc., have been described by several Continental writers.

The mountains near Nagyag consist of intrusive andesitic and trachytic rocks of Miocene age (Fig. 34).

These rocks break through the Miocene sandstones, conglomerates, and clays ; and in the mining area large inclusions of sedimentary rocks are found in the igneous material.

The andesitic rocks comprise normal hornblende-andesite and quartz-andesite or dacite with augite, hornblende, and biotite.

These rocks have been altered by various actions. At the surface they are weathered and decomposed,
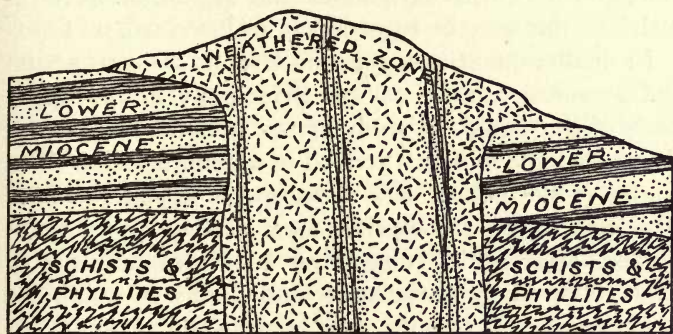
Volcanic plug of dacite, kaolinized and propylitized in the vicinity of fissures containing tellurides of gold.

FIG. 34.—IDEALIZED SECTION OF VOLCANIC MOUNTAIN AT NAGYAG, HUNGARY. (AFTER VON INKEY.)

while lower down they are propylitized and kaolinized. The kaolinization is extreme near the actual veins. The ferromagnesian minerals are changed to chlorite and carbonates, and magnetite is changed to pyrites.

The veins in the dacite of Nagyag are formed of numberless small intersecting fissures, with a general parallelism in a north and south direction. These are intersected by a series of barren crush-zones of different

ages, containing clayey and sandy material, and brecciated fragments of the country-rock.

The vein-materials vary in different parts of the district. In one part they are characterized by tellurides (nagyagite, etc.), associated with carbonates of lime, iron-magnesia, and manganese, with some tetrahedrite and pyrite (Mount Szekeremb) ; in another, by tellurides, quartz, with sylvanite, fahlerz, and a little free gold (Mount Hatjo) ; and in a third part by sulphides of lead, zinc, and iron, with carbonates and argentiferous tetrahedrite ; this may be regarded as an intermediate type.

In smaller quantities, gypsum, arsenic, and antimonial and arsenical minerals, occur principally in the upper parts of the veins. A study of the mineral paragenesis shows that the minerals arrived in a definite order. The quartz is the oldest, but it reappears at later stages. The next infilling comprises most of the common sulphides, after which come the tellurides and native gold, followed by carbonates, and finally by sulphides of antimony and arsenic, with barytes and gypsum.

The telluride-gold ores of the ancient mining district of Verespatak occur in rocks consisting of dacite, rhyolite, and volcanic breccias, interbedded with Eocene and Cretaceous sandstones.

The veins contain quartz with free gold, further characterized by the presence of carbonates of lime and manganese, the sulphides of lead, zinc, copper, and iron, and tellurides.

At Offenbanya there are two modes of occurrence of the ores. In one case the deposits exist at the contact of crystalline limestone bands, in the garnetiferous mica schist, with Tertiary andesite and dacite, and in the other case as veins.

The contact deposits consist of sulphides of iron, zinc, arsenic, and lead, with carbonate of lime, and are apparently independent of the veins.

The veins are very small, and occur mainly in dacite. The lode material consists of gold and telluride ores (nagyagite and sylvanite), with quartz, calcite, sulphides of iron, zinc, arsenic, etc. Bournonite, tetrahedride, and other complex minerals also occur, with rarer minerals including barytes and wulfenite.

Gold with Silver. — The auriferous silver group, characterized by the presence of the minerals already mentioned in the introduction, and constituting a link between the gold, silver, and the baser sulphidic veins, is represented in some of the finest mines in the world.

The famous Comstock lode, which traverses the enormous masses of Tertiary eruptive rocks between the Sierra Nevada and the Rocky Mountains at Virginia City, is about four miles in length, the ore occurring in irregularly distributed, but rich, bonanzas. It is made up of numerous veins, and fault breccias with a quartz matrix. The region is one of Tertiary volcanic activity, and the rock in which the lode principally occurs is propylitized pyroxene andesite, traversed a little to the east by propylitized mica-hornblende andesite, the junction of the two rocks being parallel to the lode.

The principal veinstone is quartz, with a little calcite and gypsum, and occasionally zeolites.

Below the outcrop the silver occurs as ruby, and native, silver ore, silver chloride, and polybasite. Rarely gold occurs. Subordinate in value are the sulphides of copper, lead, and zinc, which occur in friable quartz. The gold content of the ore varies from

0·001 to 0·05 per cent., and of the silver from 0·05 to 1·75 per cent.

The lodes of the San Juan Mountains and other places in Colorado (Ouray, Telluride, etc.), as well as near Rosita, are connected with Tertiary eruptives. At Ouray the gold ores occur in veins traversing quartzite, the richest portions being near overlying bituminous shales (60 feet thick), which in turn are overlain by Tertiary volcanic rocks.

The gold occurs in clay in veins containing quartz, secondary oxides, sulphate and carbonate of lead, iron pyrites, and a little barytes.

Near Telluride the famous Smuggler Vein is more regular in character than the Comstock lode, and is in a fault traversing augite andesite, and andesitic tuffs and breccias; its width ranges up to 5 feet or more. The mineral paragenesis is quartz, carbonate of manganese and lime, dolomite and fluorspar, with some barytes. The ores are rich in silver, and consist of proustite, polybasite, with sulphides of iron, copper, lead, and zinc, and some native gold, the content of the last being 0·0016 per cent., and of silver 0·04 per cent.

At Rosita the veins are in gneissose and granitic rocks, overlain by a series of Tertiary eruptive mica-hornblende andesites, agglomerates, and ashes, the lodes occurring sometimes, as at the Bassick mine, in volcanic plugs. The mineral association is similar to that mentioned above.

For the auriferous silver-ores of Pinehill, California, see p. 133.

The Mexican examples are principally remarkable for the connection of the rich secondary ores of silver and gold in the 'colorados' (or minerals of the

upper parts of the lodes) with the Tertiary eruptive rocks.

In the State of Oajaca, for example, the veins are in andesite, and consist of quartz with various carbonates and fluorspar. In the ' colorados ' occur chloride and bromide of silver, with other secondary ores of silver and gold, while in depth, in the ' negros ' or unaltered zone, are sulphides of zinc, lead, copper, and iron.

The veins of the famous Rosario mine in Central America (Honduras) are in connection with rhyolitic intrusions traversing Triassic sandstones and limestones; the mineral paragenesis is similar to that mentioned on the opposite page.

The well-known gold mines of the Thames district and Coromandel Coast in North Island (New Zealand) have peculiarities similar to those of Comstock, for they are connected with propylitized andesites, dacites, andesitic tuffs and conglomerates of Tertiary age. The district comprises the Hauraki gold region, Waihi and other mines.

The Thames district is intersected by two large Pliocene faults, which divide the region into three sections. The lodes consist mainly of quartz, and they are associated with numerous strings of the same mineral. The gold occurs in sugary quartz in the form of thread-, foil-, and grain- gold. The other minerals are mainly pyrites, sulphides of copper, zinc, arsenic, and antimony, while galena and tellurides of gold also occur in subordinate quantity.

The European examples of gold-silver veins have received much attention from Continental geologists, and, as in the case of the sulphidic silver-lead veins, it is on their work that the present classification of these types of ores is largely based.

In the Eastern Tyrol, near Gastein, narrow quartz veins or strings traverse gneisses and schists, and contain, in addition to gold and the common sulphides of baser metals, stibnite, molybdenite, and rich ores of silver. Pyrites is the commonest sulphide. In addition, some localities show the presence of calcite and fluorspar, and also zeolites.

In the Hungarian ore-mountains, the deposits of Schemnitz, Kremnitz, Hodritsch, and other places, occur in veins cutting rocks of so recent a period as the Miocene. The region is mainly composed of Triassic limestones and quartzites, overlain by Eocene shales. These rocks are penetrated by a series of igneous rocks, commencing with pyroxene andesites, followed by diorite, aplite, biotite and hornblende andesite, and finally by felsite, the last of which is the most abundant of the eruptives accompanying the building of the Carpathian Mountains. The andesites have been propylitized, silicified and impregnated by pyrites. The lodes, which are composite in form and ill-defined, consist of quartz, calcite, dolomite, barytes, carbonate of iron and manganese, and gypsum.

The metalliferous minerals comprise various sulphides of silver (argentite, stephanite, pyrargyrite, polybasite), and native silver and gold, the veins being further characterized by stibnite, fluorspar, cinnabar, copper sulphide, pyrrhotite, and felspar. Galena, zincblende, and auriferous pyrites, are important constituents.

In the Piedmontese Alps auriferous silver-lead ores with carbonates, quartz, and sulphides of the baser metals, are found in lodes, and as interbedded veins, in crystalline slates which are traversed by basic intrusions.

In Chi-li Province (China) the gold veins are of the

pyritic quartz type, and occur either as narrow lodes with banded structure, or as gash veins. Limestones in this district are also locally impregnated with gold near the veins.

PRIMARY COPPER VEINS.

The numerous ores of copper fall commercially under four heads, each kind of ore being characteristic of some genetic type, but not necessarily restricted to it. The *native* copper ores are either metamorphic or metasomatic, and are secondary deposits in the upper parts of veins. These two types are represented in the Lake Superior copper mines and in the gossans of lodes in South America respectively. The *oxidized* ores, which include the carbonates and silicates of copper, are low-grade secondary ores, often metasomatic, which for economical smelting are generally mixed with pyritic copper ores to get a matte, gypsum sometimes being added for the same purpose. The principal copper ore is the *sulphide*, which can be worked when containing as little as 2 per cent. of copper. This constitutes by far the most important of the copper ores of the world, and is of both primary and secondary origin. Finally there are the *complex* copper ores, which contain variable quantities of lead and zinc, which greatly detract from their value. Bismuth, antimony, arsenic, selenium, and tellurium, are rarer elements entering into the composition of some complex copper ores.

The group here considered, although very widely represented throughout the world, does not comprise some of the richest copper-fields, such as Lake Superior, Rio Tinto, and others belonging to the metamorphic or metasomatic divisions. Neither does

it include the rich copper ores formed in the upper parts of veins by decomposition and redeposition of the original ores which still exist in depth.

The most important of the copper ores is copper pyrites, but from its decomposition there arises—particularly in the upper parts of lodes—a series of secondarily developed minerals comprising copper glance, native copper, oxide, carbonate, silicate, sulphate, and phosphate of copper, and other compounds. The other ores consist of compounds of copper with antimony, arsenic, and selenium, forming complex minerals. With these ores there occur quartz, carbonates of lime, iron, and sometimes manganese, and, more rarely, barytes and fluorspar.

The subdivisions of the copper group depend solely on the relative amounts of the copper-bearing minerals, so that between one type and another there are transitional forms. By far the most abundant of these subtypes is that characterized principally by the presence of copper pyrites, iron pyrites, and quartz, with the subordinate presence of selenium and antimonial compounds of copper, and carbonate of iron. These lodes occur under conditions which can be precisely paralleled with those under which the ores of lead and zinc are found, and this applies not only to the veins, but to metasomatic deposits referred to on p. 286.

When carbonates, fluorspar, or barytes are in abundance, the vein-type belongs to one of the subgroups of copper veins, while with further additions of these minerals or subordinate ores the transitional types to other groups are formed. Fahlerz with calcite and barytes, or cobalt and nickel with siderite, are such examples. A copper ore of restricted occurrence is

that which has, owing to its objectionable nature, only been worked extensively in recent years by an improved processes of smelting. The mineral is known as enargite ($3Cu_2S,2As_2S_3$), and occurs in veins containing, in addition, fahlerz and other copper minerals.

The occurrence of native copper as an original deposit in veins constitutes a very remarkable and exceptional type found in extensively developed deposits in the Keweenaw peninsula in the Lake Superior region.

Native Copper.—In the Lake Superior region the deposits belong mainly to a peculiar type of metasomatism, and are described under that heading (p. 290); but in association with them are true fissure infillings of low-grade native copper and other minerals. Broadly described, the central part of the Keweenaw peninsula is a thick series of conglomerates, sandstones, and beds of lava (melaphyre, see p. 290), which at the upper surfaces of the flows are vesicular, and known as 'ash-beds.' As the vesicles contain native copper and other minerals, such as calcite, quartz, and zeolites, these portions of the lavas are called 'lodes' or 'amygdaloids.' The rest of the rock is considerably altered, the ferromagnesian silicates being chloritized, while there is a development of epidote which is also found among the quartz porphyry pebbles forming the conglomerate. The native copper also occurs between the pebbles.

In the Calumet and Hecla Mine, the ore is principally worked in the conglomerate.

In addition to the occurrence of native copper in the conglomerate and the amygdaloid, the copper ores exist in fissures, a few to many feet in width, which cross the bedding from conglomerate to amygdaloid. Where

they cross the latter they are exceptionately rich. The ore is found in ordinary joints, breccias, and stockworks, the principal vein material being native copper and calcite. Various zeolites are among the minerals associated with the ores. The minerals present are largely quartz, prehnite, and native copper, from grains up to masses several tons in weight; a little native
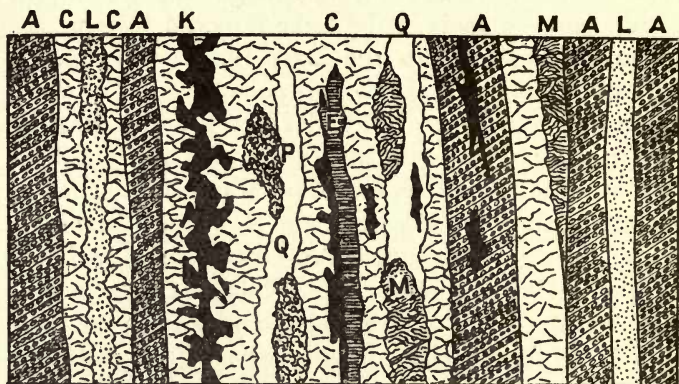
FIG. 35.—SECTION OF A COPPER VEIN IN THE LAKE SUPERIOR DISTRICT. (AFTER H. CREDNER.)

A, Amygdaloid; L, laumontite; Q, quartz; E, epidote; C, calcite; K, copper; P, prehnite; M, apophyllite.

silver is found, and orthoclase, analcime, datolite, laumontite, apophyllite, epidote, chlorite, and a little copper sulphide (Fig. 35).

The origin of the deposits is believed to be as follows: The ancient lava was much decomposed, and the ores of copper were secreted from this rock itself. The native copper was precipitated from the solutions by oxide of iron in the rock.

Similar amygdaloidal copper deposits occur in the

Transbaikalia, in Chili, and in Queensland. In Zwickau (Germany) native copper ore occurs in short fissures traversing quartz porphyry and tuff, in the Rothliegende which overlies basaltic lavas.

In Rhodesia (Victoria district) amygdaloidal basalts contain native copper and glance; cupriferous amygdaloid containing 10 per cent. of copper and a little gold is found in Zambesia.

The native copper has probably been formed by precipitation from solutions.

Sulphidic Copper Ores.—There are several important examples of pyritic copper-ore deposits in South Australia, of which the famous Wallaroo is among the best known.

The veins, which vary up to 30 feet in thickness, consist mainly of quartz, copper pyrites and some iron pyrites, with hæmatite and molybdenite. They occur in mica schists of Cambrian age, which are overlain by a recent deposit of quartzose limestone. There is, therefore, no outcrop of the lodes. Below the limestone, the lodes in their upper part show secondarily deposited minerals, including copper oxides, black sulphide of copper, and native copper with carbonates.

At Moonta there are five important copper veins, consisting of quartz, with copper and iron pyrites, and bornite, in porphyry which is overlain by the limestone mentioned above. The veins range up to 20 feet in width.

The Burra Burra Mine presents a good example of secondary enrichment near the surface. There are two lodes which traverse serpentinized and cherty limestones, slates and argillaceous sandstones. The ores

consist of quartz with red copper ore, which in depth gives place to sulphide of copper.

In New South Wales the Great Cobar mines are the most important copper-producers of the region. These occur in the districts of Cobar, Mount Hope, Nymagee, and other places situated in a district poor in water. The rocks are slates and sandstones of Silurian age, and the deposits occur as interbedded veins. The ore is mainly cupriferous pyrrhotite, with 16 per cent. of silica and up to 4 per cent. of copper. There is a little copper pyrites, copper glance and magnetite, while bismuth occurs in some quantity.

In the Mount Hope region, about 100 miles from Cobar, the ores are connected with diorite and andesite.

The copper deposits of California occur in four groups. Those of Shasta County are the most important, while the other districts are those of the foothills on the west of the Sierra Madre, those on the coastal range, and those in the south-eastern desert.

The deposits of Shasta County are situated near the town of Redding, at the northern end of the Sacramento Valley, where the ores occur largely in Triassic and Permo - Carboniferous lavas and tuffs (rhyolite and andesite), which are older than the granite intrusions of the region. Like the sedimentary series, the lavas have been much folded and sheared, and the ores occur as irregular sulphidic deposits, varying from a few inches to several hundred feet in width. The copper deposits in the Iron Mountain belt are the most important in this region, and consist of copper and iron pyrites, zincblende, a little bornite and copper glance. They sometimes occur as impregnations of crush-breccias in rhyolite, etc.

In the Bully Hill district the ores are met with in a shear-zone following a basalt dyke; they occur either in the dyke or at its contact with rhyolite. The principal ores are copper and iron pyrites, zincblende, a little quartz and barytes. Near the surface secondary ores, with limonite and galena, are found in abundance.

In the foothills of the Sierra Madre the lodes occur in metamorphic schists and slates, sometimes accompanied by quartz porphyry. The ores exist as a series of lenticular masses of copper and iron pyrites, with a little zinc ore.

In Beaverhead County, Montana, the copper ores occur in crush-zones between granite and contact altered limestones, in association with much clay, and consist of copper and iron pyrites and copper glance.

In Alaska (Copper Mountain region) deposits of copper occur in metamorphosed garnetiferous limestones in the neighbourhood of greenstones and granite. The ores exist as bands in the altered limestone in association with quartz, garnet, epidote, and magnetite; they consist of copper and iron pyrites, pyrrhotite and other sulphides. In the region of Prince William Sound, lenticular deposits of copper pyrites, iron pyrites, and pyrrhotite with quartz and pieces of the country-rock, occur in schistose rocks in the vicinity of granite, aplite, and schistose altered basic dykes and lava-flows (Fig. 36).

In the Copper River district near Mount Wrangell, the ores of copper are found as disseminations of bornite and as veins of copper glance associated with magnetite and pyrrhotite, in masses of greenstone which extend for nearly 300 miles in length. The greenstone, together with Permian limestone which sur-

rounds it, is lifted up, and forms part of the Alaskan range.

The igneous rock, which is intrusive, consists of felspar, pyroxene, chlorite, with a little serpentine and
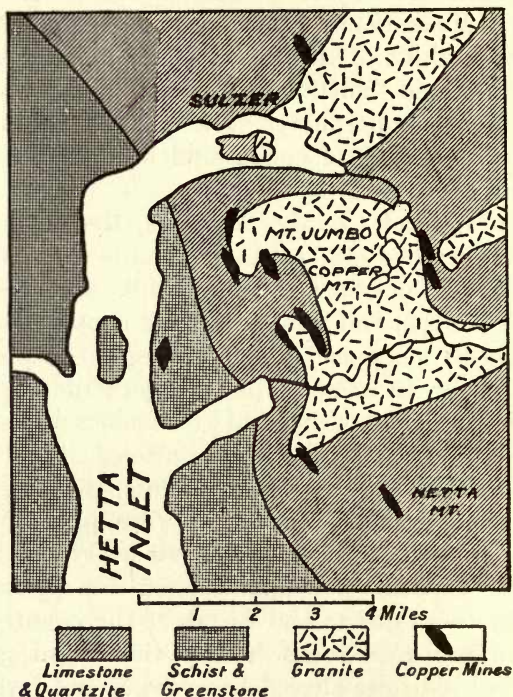
FIG. 36.—SKETCH-MAP OF THE COPPER MOUNTAIN DISTRICT, PRINCE OF WALES ISLAND, ALASKA. (AFTER F. E. AND C. W. WRIGHT.)

magnetite. Native copper and oxide of copper occur in shear-zones, while disseminations and shoots of bornite and black sulphide of copper are met with at the junction of the limestone with the greenstone. In

some parts native copper occurs with quartz in veins and with epidote as infillings of vesicles; and also at the junction of the greenstone with limestone.

In Mexico the ores of copper are associated with Tertiary granites, andesites, rhyolites, dacites, tuffs, and breccias. Auriferous copper veins are found in connection with Tertiary diorites and aplites in several countries. The ores consist of sulphides of copper with quartz and zeolites.

The Cananea Mountain district, in Sonora, is composed largely of white granite and porphyry intruded into Palæozoic limestones and quartzites. The ore deposits occur in zones of faulting and extensive fissuring.

Copper ore mixed with zinc and lead ores is found at the contact between diabase-porphyry and metamorphic garnet-epidote-limestone. Impregnations of copper ores and iron pyrites in granite and porphyry also occur. Andesite is altered to sericite and chlorite, with carbonate of lime and oxides of iron and titanium.

At Los Pilares the hill is mainly composed of a much fissured monzonite, containing low-grade copper ores and iron pyrites, but the ores are only worth working locally.

In Arizona copper is principally obtained from Bisbee, Graham (Clifton-Morenci), Gila, and Yavapai Counties.

The deposits of Bisbee are of contact metasomatic origin in limestone, and are described on pp. 288, 354.

Like those of Bisbee, the deposits of Gila County are metasomatic replacements.

In Clifton-Morenci district (Graham County) the sedimentary rocks consist of Palæozoic quartzites and limestones overlain by Cretaceous sediments and volcanic andesites and basalts. These overlie Archæan

granites, and are invaded by granite-porphyry. The ores, consisting mainly of copper glance, copper pyrites and secondary basic sulphates of copper, occur as contact deposits containing large amounts of oxidized ores, as veins and impregnations in rocks near or in the porphyry, or as veins in dolerite dykes. The contact deposits in limestones are referred to on p. 354. The ores of the veins in addition to copper pyrites consists of zincblende, molybdenite, and iron pyrites. These ores occur also as pyritic impregnations in the granite-porphyry, and much of the ore in the upper levels is oxidized.

The copper ores of Yavapai County consist of copper pyrites and zincblende, with a good silver and gold content, in a carbonate veinstone. They are found in sheared diorite near its contact with Algonkian schists. A variety of secondary ores are also met with, including carbonates of copper impregnating chert; chrysocolla is also found, and copper ores occasionally form the matrix of limestone-breccias.

The copper deposits of Wyoming are mainly of interest on account of the forms taken by the deposits. The region consists of Cambrian quartzites, conglomerates, shales, and limestones, with granite and hornblende schists intersected by dykes of diorite. At the junction of the schists with quartzites occur deposits of copper pyrites, copper glance, covellite, and other minerals. The quartzite is brecciated and traversed by numberless intersecting joints, so that, while the ore has a well-defined wall against the schists, it impregnates the quartzite in the form of interlacing strings, and gives the ore body a most irregular boundary (Fig. 37).

Chili is one of the important copper-countries of the world, but mainly as regards secondary ores, which are described later in Chapter VIII. Briefly, the copper ores of northern Chili consist of siliceous copper-pyrites veins cutting through syenite, porphyry, and
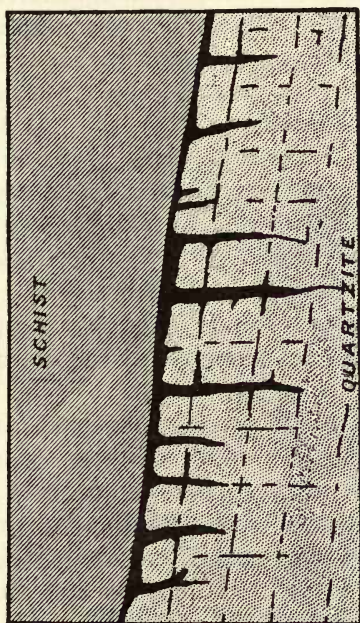
FIG. 37.—FORM OF COPPER ORE LODE IN FERRIS HAGGERTY MINE, WYOMING. (AFTER SPENCER.)

basic intrusives. Copper pyrites in the lower portions of the veins is associated with bornite, which carries a small proportion of gold; but in the upper, oxidized, zones carbonates and silicates of copper are the most productive ores, the sulphides being only low-grade.

In Central Chili the ores are mixed sulphides of

copper, lead, and zinc, with veinstones of jasper, and sometimes calcite, traversing augite porphyry. The same general conditions as regards the secondary nature of the bulk of the ores hold good for the principal Peruvian mines (Cerro de Pasco), which have also been among the most famous of silver-producers. In Peru, however, a type of copper deposit occurs in which iron and copper pyrites are found, in association with manganiferous siderite, in lodes traversing schists, quartzites and limestones.

The Italian copper deposits are confined to the district of Tuscany and Liguria. The deposits of the Massa Marittima occur filling late-Tertiary fault fissures of considerable width. The country-rock is silicified or, in its calcareous portions, altered to pyroxene-epidote rock, and impregnated by copper and iron pyrites, galena, and zincblende; the ore carries 3 per cent. of copper.

The deposits appear to be connected with intrusions of granite, but the granite does not occur in the district itself, the nearest mass being some miles away. Gabbro and diabase form subordinate intrusions. The rocks in which the deposits are situated are dolomitic limestones of Rhætic, and Lower and Middle Liassic age; also Upper Lias shales overlain by Eocene (nummulitic) limestones, sandstones, shales and marls; the remarkable veinstone is a direct product of the alteration of the calcareous beds. Metasomatic deposits of argentiferous galena, zincblende, silver-bearing fahlore, and copper pyrites, with calamine, quartz, calcite, fluorspar, and gypsum, have been worked in the past in the Liassic limestones.

The copper deposits of Monte Catini occur in the

serpentinized portions of gabbro and diorite intrusions, which pass locally into lherzolite or enstatite-augite peridotite (Fig. 38). The gabbro is in the form of laccolites intruded into Eocene limestones and shales, but the ores are entirely confined to brecciated and serpentinized portions, and appear to have been derived from the rock itself during its serpentinization. The ore exists as irregular bodies, and is composed mainly of copper and iron pyrites, with rarely a little lead and zinc sulphide.
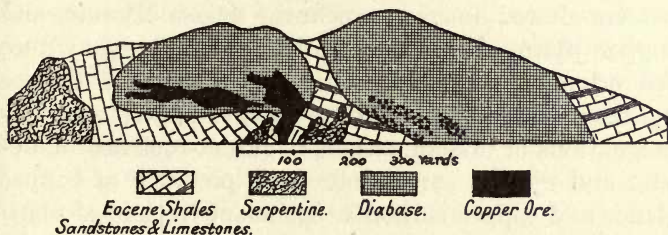
FIG. 38.—LONGITUDINAL SECTION OF THE COPPER LODE AT MONTE CATINI. (AFTER A. SCHNEIDER.)

At Coritza, near Kharput, in Asia Minor, the copper ores are similar in genesis to those of Monte Catini.

In Coro Coro, Bolivia, native copper with copper glance and arsenate of copper is found impregnating highly-inclined calcareous and ferruginous sandstones, conglomerates, and shales. The ores are believed to have been introduced from fissures.

A good deal of copper is obtained as a by-product of the silver mines in Bolivia from the mineral tetrahedrite, which is associated with such ores as sulphides of iron, copper, zinc, and lead, in a barytes-quartz veinstone.

In Cuba, near the town of Cobre, the copper ore is

obtained from quartz veins in a mineralized zone, traversing volcanic breccias interbedded with lavas. The ores consist of iron pyrites and copper pyrites, frequently coated with covellite, in a siliceous veinstone. Other kinds of deposits occur in zones of fissuring and crushing in serpentine, but their importance is less than those described above.

The island of Hayti in the West Indies contains a few deposits of copper connected with basic igneous intrusions. The veins are in dykes of diorite and in contact-altered limestones near the dykes. Bornite and copper pyrites, with some gold and silver, constitute the principal ores. Elsewhere in the island copper pyrites is found in pockets, small masses, and impregnations or disseminations in garnet-rock near andesitic and dioritic intrusions. The presence of copper glance and copper carbonate in melaphyre, and of platinum and osmiridium in the ores of copper, makes the deposits somewhat analogous to the covellite deposits of Wyoming.

At Kedabek, in Transcaucasia, deposits of copper ore are met with at an elevation of nearly 6,000 feet in the copper-mountain of Mio Dagh ; the ore is in the form of lenticles in a quartz porphyry, which is cut by dioritic dykes. In more immediate connection with the deposits is the rock known as ' kedabekite,' a garnetiferous felspar-pyroxene rock.

The ores are pyritic, but some copper glance and covelline occur, the ore bodies fading off at the sides into the country-rock in the form of veins. Zincblende is also present, and very little galena. The most characteristic veinstone mineral is barytes, but quartz is also represented.

Lodes of copper and iron pyrites, tetrahedrite, bornite, and native copper, with galena and zinc sulphide, are found between the Caspian and the Black Sea in andesite and diabase, in the form of impregnations of crush- and brecciated zones.

There are many large copper-districts in the Urals and Siberia. The principal Russian localities are on the western side of the Urals, in the neighbourhood of Perm and Nizhne-Tagilsk. The ores are mainly low-grade oxides and carbonates, in veins traversing Permian and Devonian slates and limestones. In depth the ores are pyritic. On the eastern side of the Urals pyritic copper ore, with calcite and quartz, is found in lenticular masses at the junction of diorite with pyroxene-garnet rock and limestone.

In Thuringia, near Saalfeld, copper ores occur in veins which fault the Permian limestone and the Carboniferous rocks. The veinstones consist of barytes and siderite, with a little quartz, and are richest in those parts of the lodes which traverse the Kupferscheifer. In the same region much fluorspar is found in similar veins, while hæmatite derived from the alteration of spathic iron ore has been worked.

The Spassky copper mine is situated about 200 miles south of the town of Smolensk, in the province of the same name, and is one of the most important mines in Siberia. The ores are mainly bornite, with glance and grey copper ore. They occur in veins from which the sandstone of the country-rock has been much impregnated. The vein-material is quartz and barytes. The only rocks of igneous origin in the immediate district are porphyrite and rhyolitic breccias.

In North-Western Servia copper ores are met with in

connection with serpentines intruded into Mesozoic rocks. The copper ores are composed of copper and iron pyrites, with calcite and serpentine. The ores originated by lateral concentration during the serpentinization of the rock, and are now found in brecciated masses and irregular veins.

The copper ores of South Africa are largely obtained from Namaland, or Namaqualand, in the north-west portion of Cape Colony. They are copper pyrites and bornite, and appear to be intimately connected with north-north-east dioritic dykes traversing schists and gneiss. The ores are probably segregations. Similar deposits are found in Damaraland.

In the southern part of the Congo Free State, about 100 miles north of Rhodesia, the deposits of copper ores are stockworks and impregnations of copper and iron pyrites, occasionally with manganese, in lower Palæozoic quartzites and limestone. The upper parts of the lodes contain oxides.

The ores are very siliceous, and occur largely as impregnations of quartzite by malachite. Seams of the same mineral also exist in the quartzite. The copper ores are met with along a zone of fissuring which extends in a north-westerly direction for 200 miles.

In Rhodesia copper ores have been worked for ages, but not in a large way. In the Sable Antelope mine the lodes traverse gneiss and vesicular basalt, and contain copper pyrites, glance, and carbonate, also bornite, with calcite and gypsum.

In China copper ores occur in the provinces of Yunnan and Kweichou, in both of which the sulphide is the principal ore, and is found in sandstones near masses of porphyrite and melaphyre, and in limestones.

The so-called 'white copper' prepared in this country is an alloy of copper, gold, and silver, with occasionally some nickel.

The Indian localities for copper ore are mainly distributed along the foot-hills of the Himalayas from the Punjab to Darjiling. In North-West India copper deposits are met with, for a distance of fifty miles, among schists and talcose rocks, but occasionally at the junction of limestones with the metamorphic rocks. The ore, which is mainly chalcopyrite, tetrahedrite, copper carbonate, and some bornite, is met with in veins and breccias.

Much of the copper of Japan is obtained as a by-product from silver and gold mines, but important copper deposits also occur as lodes, impregnations in igneous rocks, and lenses in schists.

The mines of Kosaki, situated in the northern part of the island, were formerly worked for silver, but now yield copper in abundance. The ore exists as impregnations of volcanic tuffs and conglomerate by iron and copper pyrites, and some zincblende; it generally occurs near dacitic or felsitic intrusions.

There are several qualities of ore. The pyritous ores contain about 1·8 per cent. of copper. The so-called 'black ore' is a mixed zinc and copper ore, containing 2·2 per cent. of copper and 15 per cent. of zinc, some silver and gold, in a veinstone containing barytes. A low-grade siliceous ore is also met with.

The Aschio mines, situated near the middle of the island, about 100 miles north of Tokyo, are the richest in Japan. The ores, which consist of iron and copper pyrites in quartz, are met with in numerous intersecting veins. They occur mainly in dacite and felsite

intruded into Palæozoic rocks.   Situated near these deposits are other mines, connected with propylitized andesites associated with Tertiary rocks.   The ores are associated with specular iron ore, sulphides of lead, zinc, and silver, with quartz, barytes, calcite, and diallogite.

In the South of Japan, in the more northerly of the two islands, is the famous Besshi Mine, situated in a series of quartz, chlorite, and graphite schists. The main body of the ore is embedded in the schists, which near the ore contain the manganese epidote, —piedmontite.   The ore, which is mainly copper sulphide, occurs with iron pyrites as bands and streaks in the schists, and yields 3 or 4 per cent. of copper. The whole mass of the ore forms a body over a mile in length, and ranges from a few feet to 30 feet in width.

In other parts of Japan the ores are found in veins near granites and diorites, and also occur in brecciated propylitized andesites.

Arsenical Sulphidic Copper Ores.—Of the type in which enargite is the dominant mineral, the most important examples are those of Butte, Montana, which contains the richest copper mines in the world.   The district was originally worked, up to 1892, mainly for silver ores, but the fall in price of that metal caused many of the silver mines to be closed down.   The copper now produced contains 84 ounces of silver and 0·3 ounce of gold to the ton of metallic copper yielded.

The mineral region is entirely made up of Tertiary igneous rocks, of which quartz monzonite, known locally as the Butte granite, is the most important, and covers the largest area, being surrounded beyond the mining

centre by Cretaceous metamorphosed limestones, etc., and partly covered by andesite and andesitic breccias.

The Butte granite is cut by later aplitic veins, and intrusions known as the 'Bluebird granite.' Still later intrusions, as dykes, of rhyolite or quartz porphyry occur with the lodes. The mineralization of the area com-
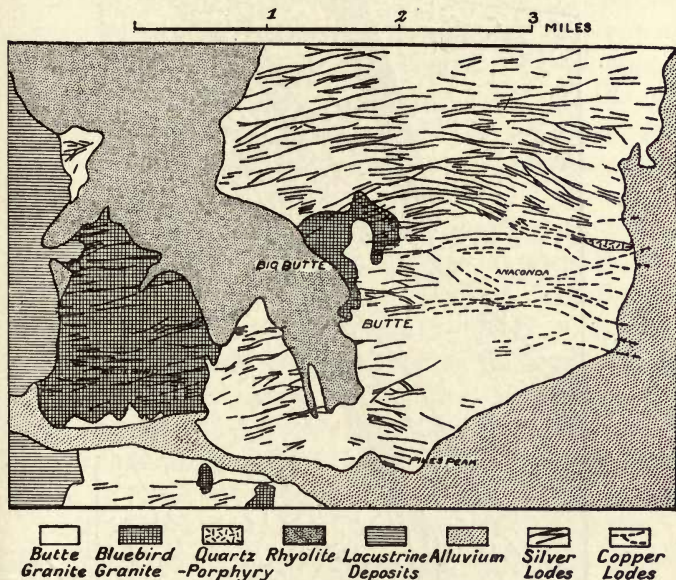
FIG. 39.—GEOLOGICAL SKETCH-MAP OF THE BUTTE DISTRICT, MONTANA. (AFTER MESSRS. WEED, EMMONS, AND TOWER.)

menced after the intrusion of the quartz porphyry, and was followed by intrusions and outpouring of rhyolite (see Figs. 39 and 40).

There are no outcrops visible, for the upper parts of the lodes have undergone extensive weathering, with secondary concentration of the ores. As pointed out in

describing the silver ores of Butte, the copper and silver areas are distinct, although all the lodes belong to the same period of mineralization. They are clearly
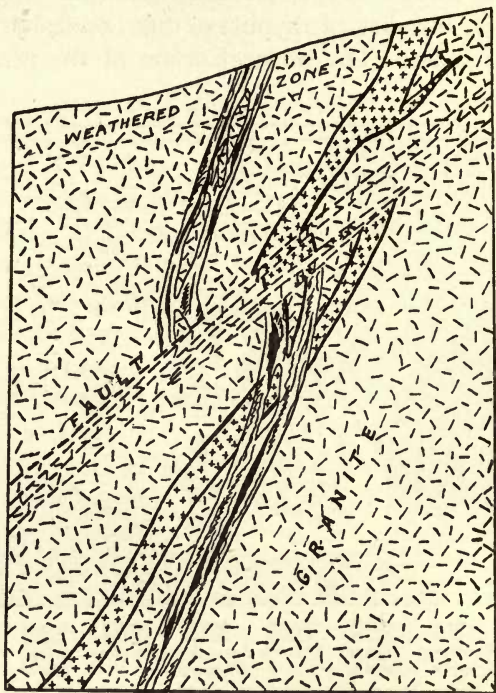
FIG. 40.—IDEALIZED SECTION OF A COPPER LODE AT BUTTE, MONTANA, SHOWING THE RELATION OF QUARTZ PORPHYRY DYKE, LODE, AND FAULT TO ONE ANOTHER. (AFTER H. V. WINCHELL.)

divisible into three groups. The oldest is that upon which the famous Anaconda is situated, having an east and west strike. This is intersected by another rich group of lodes, with a bearing north-west and south-

east.   The youngest system contains but little ore, and this is mainly brecciated material from the lodes it traverses.   The direction of the last is north-east and south-west.

In the copper lodes of the district of Butte the ores, to a depth of 400 feet are, according to S. F. Emmons, largely of secondary origin, but in depth are composed of enargite, copper glance, and bornite, with pyritic quartz.   Covellite, grey copper ore, and copper pyrites, are also found.   Ten per cent. of the ore averages 6 per cent. of copper, while the rest varies between 2 and 4 per cent.   Gold and silver are yielded by the mines of the region.

The ores appear to be partly replacement deposits in fractured granite near lodes, and in this respect differ from the silver ores.   Enargite is one of the principal original minerals, for it increases in quantity with depth.   Similar deposits are found in Utah (Tintic Mines).   Enargite, with tetrahedrite, tennantite, and luzonite, containing from 10 to 33 per cent. of metallic copper, and from 1 to 6 dwt. of gold, to the ton, are met with in the Philippines.

In the Sierra Famatina (Argentine) and at Luzon, in the Philippines, veins of enargite ($CuAs_4S$) and famatinite ($CuSb_4S$) occur as the principal cupriferous deposits.   Near the surface quartz and barytes with ores of silver and gold were found; but in depth the enargite made its appearance, with other sulphides, antimonides, and arsenides.

In the Philippines similar ores occur, together with selenium compounds of silver and copper, and the usual secondary minerals.

The Argentine locality consists of metamorphic slates

cut by dykes of porphyry. The ore occurs in fissures traversing the slates in every direction. The upper parts of the veins consisted of oxidized ores and carbonates, below which were complex ores, such as enargite, famatinite, eucarite, humangite (selenide of copper and silver), and copper glance, but in depth these diminished. Galena and zincblende occur in some quantity.

PRIMARY LEAD AND ZINC VEINS.

Deposits of galena and zincblende fall within important subgroups, and have such marked differences in form and mode of deposition that it is convenient to deal with them under the heads of fissure or vein deposits and metasomatic deposits. In this section, only the veins will be described. The ores of lead and zinc have an identical mode of occurrence, and they are commonly associated with one another, the ores of lead sometimes giving place to ores of zinc and *vice versa*. Although often characterized by a variety of other minerals, their various vein-types are comparatively simple, and are in marked contrast to the ores of gold and silver. In many respects, however, the lead veins from the genetic standpoint are inseparable from those of silver, as the difference is only that of the relative proportions of these ores to one another.

Galena usually contains a small percentage of silver, varying from 0·02 per cent. up to 2 per cent. in the different subgroups into which the veins are divisible.

Other metalliferous minerals found in association with lead and zinc ores include sulphides of iron and copper, with compounds such as bournonite, fahlerz, jamesonite, antimonite, and very exceptionally also

nickel, cobalt, and bismuth ores. Mispickel is occasionally present, and sometimes phosphates. ˙Cadmium is commonly, and indium and gallium are rarely, found associated with ores of zinc.

Minerals which characterize ores of pneumatolytic origin are absent, although microlites of tinstone (cassiterite) have been detected in zincblende at Freiberg, and wolfram in lead ore in the Hartz and in Cornwall.

The veins of lead and zinc appear to be connected with acid intrusive rocks of all ages, but the ores not infrequently show a marked preference for certain kinds of rocks.

In the younger or Tertiary intrusives they almost invariably contain appreciable amounts of gold and silver, often in such quantity as to warrant their classification with the gold and silver veins.

The most important lead and zinc lodes are those which occur in the Palæozoic rocks.

The generally accepted classification of lead and zinc lodes is dependent upon some dominant vein constituent, which leads to a threefold grouping.

The first is the pyrites-lead-quartz group, which includes such minerals as galena, zincblende, iron and copper pyrites, mispickel, and quartz. Subordinate amounts of carbonate of lime, magnesia, and iron, with jasper and chlorite, may also be present. ˙The amount of silver present in the galena rarely exceeds 0˙5 per cent., and is generally from 0˙1 to 0˙2 per cent., while it is absent in the other minerals.

The second group comprises veins consisting of rich argentiferous lead ores (galena), with brown spar (dolomite) as the most important veinstone. The other minerals present may be quartz, zincblende, iron pyrites,

fahlerz, rich silver ores, carbonate of iron and manganese. The pyritic constituents may also be argentiferous, and there are sometimes argentite and ruby silver ores. The amount of silver in the galena varies from 0·4 per cent. to 2 per cent. In the zincblende silver in the form of sulphide may be present to the amount of 1·5 per cent., while the pyrites may contain as much as 0·2 per cent.

The third group is that of the barytic lead veins, in which barytes is the main vein constituent, usually accompanied by quartz, calcite, and fluorspar of various tints. The metalliferous minerals are argentiferous galena, sulphides of iron, zinc, and copper, with fahlerz and rich silver ores. The zincblende frequently contains inclusions of silver sulphide, and the galena contains from 0·02 to 0·08 per cent. of silver.

All these three types of veins occur in the Freiberg district, where, in addition to the simple forms, there are transition-types having the qualities of two or more groups.

Typical Examples of Lead and Zinc Veins.—The lead and zinc veins of Cardigan and Montgomery occur in a belt twenty-two miles in length, extending from the south of Cardiganshire to Llanidloes, in Montgomery. No igneous rocks exist anywhere in this district, so that the source of the ores, although probably deep-seated, is unknown.

There are six groups of lodes corresponding with undulations in the Palæozoic shales, grits, and conglomerates. In the west the lodes consist of slightly argentiferous galena with zincblende, and occasionally sulphide of copper. The rich district known as the Welsh Potosi yielded argentiferous galena containing

38 ounces of silver to the ton of lead from lodes up to 20 feet in width. The quantity of iron pyrites in some parts of the district is remarkable. The chief veinstones consist of quartz, a very little calcite and chalybite ; but in the east, near Llanidloes, some witherite and barytes occur. The layers in the lodes show that calcite was deposited before the quartz, and the galena before the zincblende. The veins have an east-north-east strike and a southerly dip.

In Denbighshire (Minera) the lead veins are in limestone, the order of deposition of the vein materials being quartz, galena, blende, calcite, copper and iron pyrites, and calcite ; but this order is somewhat variable, and elsewhere it is blende, quartz, galena, calcite and copper pyrites.

In the Isle of Man the deposits of lead ore are associated at Laxey with the granite-mass situated between it and Ramsey, and at Foxdale with a second granite-mass near South Barrule. At Laxey the veins are in pre-Silurian slates, while those of Foxdale are in granite. Porphyry, diabase, and other hypabyssal rocks also exist in the district.

The principal lode at Foxdale ranges up to 40 feet in width, and contains rich argentiferous galena. Argentiferous fahlerz and some iron pyrites occur, and a little plumosite is recorded. Quartz is the characteristic veinstone, but carbonate of iron pseudomorphs after fluorspar occurs as a significant vein-accompaniment.

At Laxey zinc and copper sulphides are met with in the lead veins.

The lead ores of the West of England have not been worked for many years. They are distributed in various districts in Devon (Ilfracombe, Tavistock, Oke-

hampton, Beeralston), and in Cornwall (Calstock, Callington, Menheniot, St. Minver, St. Teath, Endellion, Newquay, Truro, Perranzabuloe, Helston).

The ores appear to belong to the barytes-fluor-quartz type, although neither barytes nor fluor are universal. Near Tavistock the ores consist mainly of sulphide of lead and zinc, with carbonate of iron, oxide of iron, and quartz. At Beeralston a siliceous veinstone contains argentiferous galena.

The lodes of Wheal Mary Ann, in Cornwall, show a characteristic paragenesis. The veinstones are banded, and sometimes associated with brecciated killas cemented by chalcedonic quartz. There are two periods of infiltration of fluorspar, with an intervening period in which quartz and galena were deposited, followed, finally, by deposition of quartz, iron pyrites and calcite. Carbonate and phosphate of iron and lead occur with native silver, red and dark sulphide of silver, some copper sulphide, antimonial ore, bournonite, and barytes. Zinc sulphide is found at Herodsfoot. In North Cornwall antimonial silver and lead ores occur, but their connection with the lead ores of East Cornwall and Devon is doubtful.

Near Truro the veins consist of quartz, galena, and zincblende, while near Helston carbonate of iron, iron pyrites, and pyromorphite, exist in association with the lead and zinc sulphides.

The lead deposits of Northumberland, Cumberland, Durham, and Derbyshire, are generally found in limestones, which are metasomatically replaced by lead ores near the lodes, so that they are usually metasomatic replacements, but in some cases are infillings of cavities formed by the solvent action of water. In the Alston

district (Northumberland) the lodes are found mainly in the Carboniferous limestone, but are particularly productive in certain beds. In addition to fluctuations in productiveness, there are often marked changes in the mineral contents of the lodes. In some places the characteristic minerals are fluorspar and calcite, while in others they are spathic iron ore or brown hæmatite ('scar' limestone).

In Derbyshire the variety of forms displayed by the ore bodies has led to their classification under such terms as 'rakes,' 'pipes,' 'flats' and 'scrins.' The rakes are true fissures, often faults; the scrins are mineralized fissures crossing them; the flats are mineralized bedding planes; while pipes are irregular pipe-like bodies of ore.

At three horizons in the Derbyshire limestone are sheets of basaltic rocks, known as 'toadstones.' When the lodes pass from limestone into the Millstone Grit, shales, or toadstone, they become unproductive.

In Colorado (the Aspen, Rico, Enterprise mines, etc.) the lodes have a north-east bearing, and traverse slates, sandstones, and limestones of Lower Carboniferous age. They differ in character and vary in value according to the rocks which they traverse.

At the contact of a much-fractured limestone with overlying shales the ore has spread out laterally, and by infiltration has acquired a banded structure. Below this horizon the lodes are barren; they consist mainly of breccias ranging up to about a foot in thickness, and contrast strongly with the numerous strings in the limestone. The vein materials are quartz and carbonate of manganese, with galena, zincblende, copper and iron pyrites, also the sulphides of silver and antimony. A little native silver with gold occurs in some places.

At Plomo, Colorado, a granite-gneiss contains auriferous pyrites along certain bands and zones. These appear to have been formed by impregnation and replacement along crush-belts. Hornblende and biotite are altered to chlorite. Secondary quartz and cubes of pyrites also occur, and the altered rock passes insensibly into the gneiss. The mineral solutions traversing faults penetrated the crush-zones of the gneiss, and deposited auriferous pyrites and silica. At a later date renewed disturbance resulted in dyke-intrusions of quartz porphyry and the formation of a system of fissures, through which a second access of mineralizing solutions resulted in the formation of later lodes containing quartz, galena, copper and zinc sulphides, fluorspar, and micaceous iron ore.

The lead deposits of the Cœur d'Alene district, in Northern Idaho, between Spokane and the Bitter Mountains, belong to the carbonate type. The district is composed of Algonkian slates and quartzites pierced by a large syenitic intrusion. The lodes are later than the syenite, but older than a series of intrusive basaltic rocks which traverses it; the Hecla vein, however, is an exception, for it is younger than a basic dyke with which it is associated.

The veins, in addition to argentiferous galena (10 per cent.), contain considerable amounts of carbonate of iron, quartz, zincblende, and iron pyrites, some copper ore and barytes, and other minerals, including secondary compounds of silver (Fig. 41).

At Frisco, in Utah, the Hornsilver Mine is on a lode situated at the junction of limestone with andesitic rocks. The limestone is metamorphosed to garnet-rock by an intrusion of monzonite, which has also affected

some of the lodes of the district, so that they may be classed with metamorphic types of ore deposits.

Farther north in the same State, on the west of the Wasatch Range, near Salt Lake City, are two lead-bearing districts of disturbed Palæozoic rocks, consisting in part of limestones and quartzites. The igneous rocks are granite and quartz porphyry. The veins of

Fig. 41.—Quartzite replaced by Siderite and Pyrites. Helena and Frisco Mine, Cœur d'Alene, Idaho. (Magnified 100 Diameters.) (After W. Lindgren.)

S, Siderite; P, pyrites; Ser, sericite. In other cases galena and zincblende replace the quartz.

Oquirrh traverse Carboniferous limestone and quartzite, and consist of quartz, galena, zincblende, pyrites, pyrrhotite, etc.; near the surface they yield rich secondary ores silver and lead. At Bingham the vein-paragenesis is similar.

Lead ores have recently been worked in Ontario (Hastings County), the type being referred by Volney Lewis to the galena-calcite lodes. The ore occurs in a

lode traversing highly schistose rocks at right angles to the foliation. The associated minerals are, in addition to rose-coloured calcite-siderite, zincblende, pyrites, and pyrrhotite; ozokerite is also found, but no quartz.

In New South Wales, the famous Broken Hill Mine is another example of argentiferous galena associated with quartz, fluorspar, and small quantities of calcite. The country consists of metamorphic rocks penetrated by granitic masses and dykes of diorite. There are two principal lodes, the larger of which is nearly 100 feet wide in places. The actual rock traversed by these lodes is a garnetiferous biotite gneiss, which at Broken Hill is supposed to be bent in the form of a sharp anticlinal fold, accompanied by crushing.

Crystalline garnet may be regarded as a true vein-constituent, for it contains inclusions of galena and blende. It appears in the vein, however, to be due to a reconstruction of brecciated garnetiferous country-rock, since secondary garnet crystals are found growing on garnetiferous fragments. Intergrown with the garnet is silicate of manganese.

At Zeehan, in Western Tasmania, the much-folded Lower Silurian conglomerates, sandstones, and clay slates, with altered basaltic lavas and tuffs, are, in the neighbourhood of the lead veins, much altered by granite. Gabbro and serpentine are also found in the mineral district, but these are older than the granitic intrusions.

The veins are connected with the granite, and three groups, differentiated by their characteristic minerals, have been recognized. The ores occur in fissures either as thin strings or as masses reaching 20 feet in width; also as irregular deposits from 60 to 200 feet wide.

The first group contains sulphides of lead, zinc, and iron.

The second contains argentiferous galena, with a little blende, pyrites and carbonate of iron.

The third is an insignificant series which belongs to a transition-type between tin and silver-lead veins. The ores consist of argentiferous sulphide of tin, with wolfram, copper and iron pyrites, galena, sulphide of bismuth, and carbonate of iron. The galena contains from 10 to 200 ounces of silver to the ton; the argentiferous pyrites, 146 ounces to the ton.

The veins, however, of the district generally belong to a mixed type, representing the characters of the first two groups; they may also carry jamesonite, bournanite, and fahlerz.

The upper parts of the lodes contain native silver and other secondary silver ores (chlorides and sulphides), oxide of manganese, sulphate and carbonate of lead, etc., while the veinstone is generally quartz, with subordinate amounts of calcite, dolomite and carbonate of iron.

In the Dundas region, six miles east of Zeehan, the deposits are similar, but in some cases show a departure from the usual type, as, for instance, in the connection of sulphidic minerals and carbonate of iron with dolomite.

In the Freiberg district (Saxony) the lodes are situated mainly in gneiss, mica schists, quartzites, and other metamorphic rocks. Eclogites, garnetiferous hornblende rocks, serpentine, and gabbro, also occur.

These rocks are broken through by granite, and by quartz-porphyry and other dyke rocks. With the exception of the rich silver-quartz veins of the district,

the lodes are all younger than the quartz-porphyries, the barytic lead veins being the youngest.

The lodes may be classified according to their strike. The pyrites-lead and part of the rich silver-quartz and rich lead types strike about north-north-east, while the barytes-lead veins and the remainder of those above mentioned strike about north-west in common with non-metalliferous cross-courses.

The pyritous lead ores also are well represented in the mining-region of Freiberg, where the infilling of the veins consists of quartz, iron pyrites, pyrrhotite, argentiferous galena, zincblende, and sulphides of arsenic, copper, and other metals, with smaller quantities of the carbonates of iron, manganese, calcium and magnesium. Among other minerals may be mentioned: barytes, fluorspar, calcite, strontianite, pitchblende, and a variety of rarer minerals, together with secondary ores. The zincblende contains small quantities of tin ore in the form of microliths.

In this region a few of the lodes are characterized by an exceptionally high proportion of copper ores.

The barytes-silver-lead lodes, ranging from 3 to 12 and even 20 feet in width, occur in gneiss, phyllites, and mica-schist, and consist mainly of barytes, fluorspar, quartz, calcite, and dolomite, with sulphide of lead, copper, iron, and zinc. Bournonite is also present with less common minerals, such as arsenical pyrites, antimonial silver-blende, cerussite, anglesite, malachite, and other secondary ores. Rarely they contain nickel and cobalt ores. They are later than the pyritous and high-grade lead veins, which they traverse like faults.

At Schneeberg, in Saxony, arsenical pyrite occurs in large quantities, quite dominating the galena con-

tents of the lodes, while at Annaberg the lodes are typified by a predominance of copper pyrites. Lodes of the barytes-lead type occur at other places in Saxony, and are further characterized by the presence of calcite, quartz, and fluorspar.

At Katzbach, in Silesia, and Altenberg, in Saxony, the pyritic lead veins are closely associated with an olivine kersantite, the lodes containing fragments of the kersantite dykes and the country-rocks. The most common pyritic mineral is mispickel, which constitutes from 20 to 50 per cent. of the ore. Sulphides of copper (auriferous), lead, zinc, antimony, and other minerals, are also present.

In Nassau there are two series of lodes, known as the Ems and Holzappel Series respectively. The lodes of both series traverse the Lower Devonian shales and quartzites. At Ems the veins have north-north-west and east and west directions, the principal vein minerals being quartz, calcite, dolomite, and alteration products of siderite, with argentiferous galena and other sulphides.

The gossan is characterized by secondary ores, below which comes a zone containing fahlerz, with cobalt and nickel sulph-arsenides, etc.

The Holzappel lode is characterized by shoots ranging up to 3 feet in width, and consisting of breccias cemented by sulphides of the metals characteristic of this group, and by carbonate of iron.

A sericitic alteration of the country-rock is common.

In the gneissose region of Bohemia the mineral paragenesis is quartz, calcite, ankerite with argentiferous galena, arsenical pyrites, native silver and red silver ores with zincblende and other minerals.

In the Clausthal region (Harz Mountains) the lodes
occur in Devonian and Lower Carboniferous shales over
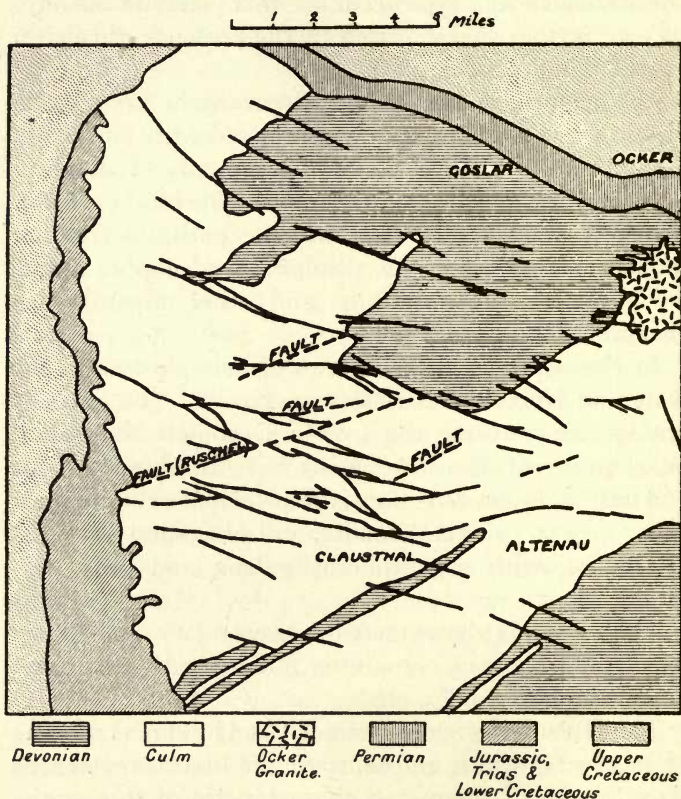
FIG. 42.—GEOLOGICAL SKETCH-MAP OF THE LODES OF THE
CLAUSTHAL REGION, UPPER HARZ. (AFTER F. KLOCK-
MANN.)

an area ten miles long by five miles wide, and belong
to the carbonate type. There are ten parallel series of
composite lodes with their numerous stringers, and

each series is traceable through practically the whole length of the mineral area (Fig. 42).

The average strike of these composite lodes is either towards the south-west, or is east and west, and they all have an underlie of from 10° to 20° to the south. The veins are later in age than the folding of the region, and can be actually seen to traverse several zones of brecciated rock (the so-called ' ruscheln '), existing along planes of overthrusting, and striking towards the north-east (Fig. 43).

The contents of the lodes consist mainly of quartz, calcite, and in some cases barytes, with lesser amounts
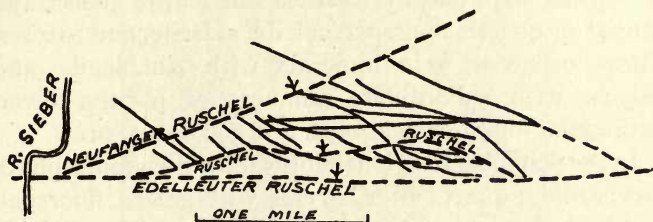
Fig. 43.—Plan of the Faults (Ruscheln) and Lodes at St. Andreasberg, Harz. (After F. Klockmann.)

of siderite, strontianite, and dolomite, with fragments of crushed country-rock. The principal ores are argentiferous galena (0·2 to 0·3 per cent. of silver), zincblende, copper and iron pyrites, tetrahedrite, and bournonite.

In the State of Anhalt, the deposits of the Harz Mountains belong to the high-grade lead ores, and consist of minerals of several generations associated with a vein of spathic iron ore of considerable width. The oldest vein minerals are quartz, pyrites, and pyrrhotite ; then comes fluorspar with spathic iron ore, some zincblende, and barytes ; thirdly comes galena

and copper pyrites, with bournonite, fahlerz, and anti-monial ores; and finally spathic iron and calcite. Wolfram and scheelite occur occasionally.

In the Rhineland and Westphalian regions there are several zinc- and lead-fields in the Palæozoic rocks. The veins are the siliceous zinc-lead carbonate type, but are occasionally characterized by barytes.

Those of Coblenz (Werlan) are of a type similar to the Holzappel lodes.

The other localities are near Arnsberg, Gladbach, Düsseldorf, etc.

In the Black Forest (Münsterthal) the lodes are associated with porphyritic dykes in biotite gneiss, and consist of quartz, fluorspar, calcite, siderite, and barytes. These occur as vein minerals with zincblende and galena, with subordinate amounts of pyrites, silver, antimonial and arsenical ores, and secondary ores.

In the Schapbach region the ores show pseudomorphs of saccharoidal quartz after barytes, with galena, fluorspar, and both original and secondary copper ores. Calcite, dolomite, and siderite also occur. Bismuth, silver, and other ores, are also found.

At Pribram, in Bohemia, lodes are found in a syn-cline of Cambrian grits, on the south-east of which are slates contact-altered by the granite-mass which lies still farther towards the south.

Between the grits and some shales lying to the north there is a fault striking north-east, which cuts off the grits against the shales. One of the principal mining centres is situated close to this fault (known as the Lettenkluft), and is traversed obliquely by the lodes; these in the shales, however, become poor.

Parallel with the lodes are greenstone dykes in which

most of the richest ores are met with. The diagram illustrates the general character of the Adalbert lode (Fig. 44).

The lodes become richer in antimony and poorer in lead ores in passing from grits to greenstone.

In their upper parts, to a depth of 200 feet, are secondary oxides and carbonates of iron, copper, and lead, with native silver.

| Greywacke | Diorite | Calcite | Quartz | Galena | Blende |

FIG. 44.—SECTION OF THE ADALBERT LODES, PRIBRAM.
(AFTER J. ZADRIZIL.)

Below this there are two modifications of the quartz-carbonate type of lead vein. In the Liegend and North-west lodes the ore consists of argentiferous galena (0·1 to 0·7 per cent. of silver), with sulphide of zinc, carbonates of iron and calcium, and quartz. Arsenical ores, barytes, and compounds of cobalt and titanium are also found.

In the Anna Mine some of the ore is highly siliceous, and contains but little carbonates, the metalliferous minerals being argentiferous galena, ruby and native silver ore, fahlerz, antimony sulphide, etc., these being younger than those mentioned above.

The lodes show a banded arrangement in which early ore of the first type occurs next to ore of the second type, with a last vein-filling of calcite.

There are several localities in Bohemia which are distinguished as zinc or lead producers.

To the west and south of Pilsen, lead and zinc ores are found with quartz. In one place the mineral paragenesis is quartz with some barytes and fluorspar, followed by sulphides of lead (with 0·02 per cent. of silver), zinc, and iron. In a neighbouring district the barytes and fluorspar are not present, but are replaced by calcite and dolomite ; the silver content of the galena varies between 0·05 and 0·2 per cent.

South of these places (at Kuttenberg), on the south-east of Prague, and at Budweis, in Southern Bohemia, veins of zinc and lead sulphide, with quartz, calcite, dolomite, iron pyrites, and sulphide of arsenic, with some native and red silver ores, occur in gneiss overlain by Cretaceous rocks. The gneiss is invaded by an intrusion of granite, and by veins of pegmatite and mica trap.

North of Graz, in Styria, in the Southern Tyrol, and on the east of Trent, veins of zinc and lead sulphides are well known. North of Graz the lodes are in calcareous, chloritic, and clay slates, and consist of zincblende and galena (with about 0·06 per cent. of silver), with sulphides of copper and iron ; quartz, barytes, silicate of zinc and carbonates of iron, calcium and barium, are common associates.

In some veins the order of mineralization was quartz, albite felspar, sulphides of zinc and lead, fluorspar, and galena of a second generation with secondary carbonates.

At Pfundererberg the gneiss and slates are traversed by diorite veins, and dykes of aplite and micropegmatite. The lodes are brecciated, and contain sulphides of lead, copper, iron, and zinc. The galena contains 0·3 to 0·6 per cent. of silver, while the copper and iron sulphides are auriferous.

In the district of Laibach, in Carniola, ores of lead and zinc occur in fissure-breccias and fractures in irregularly bedded Carboniferous sandstones and shales. Three modifications of the veins are known. The first consists of sulphides of lead, zinc, and iron, with barytes. The second is hæmatite with barytes, galena, and a little cinnabar and copper ore. The third is cinnabar in veins with limonite, barytes, aragonite, witherite, etc.

The Bosnian occurrences are associated with pro-pylitized dacite, slates, and quartzites. The lodes, ranging up to 16 feet in width, consist of quartz, with a little dolomite and siderite, sulphides of lead (0·2 per cent. of silver), zinc, and iron, and small amounts of fahlerz, antimonial copper, and secondary ores.

Tuscany and Sicily have their lead mines. In Tuscany the lodes are in Palæozoic slates, and consist of quartz, a little albite, carbonates of calcium and iron, and sulphides of lead (0·3 to 0·5 per cent. of silver), zinc, iron, and copper, with antimonial lead ores. A little tin, with cobalt and bismuth, is recorded.

Some important lead and zinc deposits of meta-somatic origin, as well as of the nature of ordinary

lodes, occur in Sardinia. The lodes occur in meta-
morphosed Silurian and Cambrian slates, sandstones,
and limestones, and are connected with pre-Triassic
hornblende granite masses having syenitic modifica-
tions, also with later dykes of porphyry and micro-
granite.

The nature of the veins at Iglesias is typical of
the occurrences elsewhere in Southern Sardinia. The
metasomatic types connected with these veins are de-
scribed under metasomasis. The veins of Monte-
vecchio, near Iglesias, occur as single or composite
lodes, varying from the thickness of a knife-edge up
to 50 or 100 feet. The veinstones are quartz with
barytes, and here and there fluorspar, which in some
places shows a marked preference for the parts of the
lodes situated in limestone. Argentiferous galena (0·08
to 0·17 per cent. of silver), sulphides of copper and
iron, with carbonates of lead, iron, and calcium, occur
with secondary, red and native, silver ores, hornsilver,
and other secondary minerals.

In the same region sulphides of lead and zinc occur
in association with sulphides of iron and copper as
impregnations in an intrusion of diabase. The ores
are accompanied by hornblende and calcite, which
appear to replace the felspar and augite of the original
rock. Transitional types between the ores and the
fresh rock are also recognized.

The deposits of the province of Murcia, in Spain,
occur in association with Tertiary dacites and augite-
hypersthene andesites, which are kaolinized and partly
altered to alumstone by the influence of sulphuric
action on the weathered rock.

The rich ores of silver and lead contain sulphides

of zinc and iron, with calcite and siderite. The lodes traverse metamorphosed slates and limestones, but in the latter the ores are of metasomatic origin.

In the Sierra Morena (near Linares), and at Ciudad, rich lead ores occur. At Linares the lodes are in granite and Silurian slates and quartzites; the Triassic rocks of the region not containing any lodes. The lead of the lead ore yields from 0·012 to 0·015 per cent. of silver.

Both at Linares and at Ciudad Real there is scarcely any zincblende or iron pyrites, and the principal veinstone is quartz. At Linares the vein materials consist of dolomite, with a little barytes and siderite; secondary ores, such as sulphate of lead and copper (linarite), and carbonate of lead, are met with. At Ciudad Real, however, there is no calcite or barytes, and the lead contains 0·4 to 0·5 per cent. of silver.

Lead occurs in several places in France. In Provence the lodes are in schists and quartzites, and consist mainly of zinc sulphides with a little galena, copper pyrites, bournonite, and siderite, in a quartzose veinstone.

The lodes of the Department of Lozère occur in granite, metamorphosed sediments, and in rocks of Triassic age. In the Auvergne they are contemporaneous with the older of the Tertiary volcanics (pre-Pliocene rhyolites), which are overlain by later lavas. The important lead veins occur in gneiss and other metamorphic rocks traversed by veins of fine-grained granite and quartz porphyry. Argentiferous galena, with sulphides of zinc, iron and copper, antimonial compounds, barytes, and quartz, constitute the principal vein materials.

Near Vefsen, in Norway, the lead ores contain from

0·2 to 0·8 per cent. of silver, and are associated with zincblende, the sulphides of arsenic, iron, copper, and antimony, and argentiferous compounds; carbonates and barytes are uncommon. The lodes are in gneiss, schist, and older Palæozoic rocks, embracing dolomites and limestones, intruded by gabbro and soda granite; the apophyses of the latter are often cut by the veins.

PRIMARY SILVER ORE VEINS.

Many of the important deposits of silver occur as secondary concentrations in the gossans or upper parts of silver-lead lodes, and do not come in the class of veins here considered. True silver-ore veins are characterized by the presence of original argentiferous minerals, comprising native silver and alloys; compounds of silver with the halogens; minerals containing silver and sulphur, tellurium, selenium, antimony, arsenic, bismuth, copper and lead, and complex compounds of these elements.

Galena nearly always contains a little silver, while other sulphides, such as mispickel, zincblende, and iron pyrites, are sometimes argentiferous.

In the classification of the various silver-ore types, the somewhat arbitrary mode of treatment which is used in the grouping of the gold ores must again be employed, since a true genetic treatment is rendered difficult by the lack of data which might enable the ores to be linked with the igneous rocks from which they were derived.

One of the most important of the subgroups of silver veins is that in which quartz, often amethystine, is a typical vein-constituent. The veins are further characterized by the presence of accessory minerals containing

cobalt and nickel. Sulphides are generally present, all of which may be argentiferous. It is to the presence of these sulphides, in a fine state of division, that the dark colour of much of the quartz is due.

Among the metalliferous minerals present are pyrites, mispickel, blende, galena, and chalcopyrite. The principal silver minerals may be silver glance, polybasite, stephanite, proustite, pyrargyrite, etc.

Of the non-metalliferous minerals which occur as accessory constituents, calcite with some carbonate of manganese, and, very occasionally, barytes, are the most important.

The principal localities where this type of vein is represented show that it is particularly associated with the younger eruptive rocks, which are frequently propylitized, silicified or kaolinized, and impregnated with pyritic minerals near the veins. It will be noticed that this subgroup has a distinct genetic similarity to that of the gold-quartz veins, and, as some of the silver ores of this subgroup contain gold, it will be readily recognized that the subtypes may be regarded as members of a gold-silver-sulphide-quartz group.

A similar remark applies to the subgroup of silver ores which is distinguished by the presence in the lodes of an appreciable amount of calcium carbonate, with accessory metallic sulphides and arsenides. The lodes have modifications in which the metals, such as silver, antimony, nickel, cobalt, and arsenic, occur native, and sometimes in association with zeolites when developed near igneous rocks.

The presence of barytes in considerable quantity, in addition to sulphidic minerals, is characteristic of some

silver veins, but of these a number are probably the enriched upper parts of lodes which in depth are rich in sulphides of lead, zinc, and copper.

Silver ores which are accompanied by considerable amounts of cobalt and nickel compounds appear to form an indefinite subgroup, in which bismuth ores occur with sulphides of lead, zinc, and copper. In addition there is often pitchblende, arsenical pyrites, and antimonite. The veinstones are commonly quartz and carbonates, with accessory barytes and fluorspar.

In the chapter dealing with deposits of pneumatolytic origin, reference was made to the occurrence of certain tin ores in Bolivia associated with pyritic silver ores, and it is questionable whether they should not be dealt with here, seeing that they may be regarded either as deposits of pyritic silver ores characterized by the presence of cassiterite, or of cassiterite characterized by the presence of silver ores and other sulphides. The comparative scarcity of minerals, such as tourmaline, topaz, and fluorspar, justifies the view that these deposits constitute an intermediate type between true tin veins and sulphidic silver veins, but, as they have already been dealt with under pneumatolysis, they are only briefly mentioned here.

Typical Examples of Silver Ore Veins.—The Butte district, Montana, has been one of the richest silver and copper producing regions in the world.

The lodes occur in a post-Cretaceous hornblende granite, known as quartz monzonite. It is the oldest of the igneous rocks, and is cut by newer aplitic or granulitic intrusions. Both these intrusions were traversed by dykes of quartz porphyry, at which stage in the eruptive history of the region the lodes were

formed; and consequently they traverse the granite, aplite, and quartz porphyry alike (see Fig. on p. 173).

The formation of the lodes appears to have taken place in two stages in which the copper ores arrived before the silver ores. At a later period there were extrusions of Tertiary rhyolites and tuffs, but in these no lodes are found.

The principal copper lodes occur in a rich but comparatively restricted area in the eastern part of the mineralized region, while the silver lodes occur principally on the north and west.

The relationship between the ores of the copper and silver groups is not obvious, for while the nature of the minerals in the two sets of veins differs somewhat in character, yet the existence of silver in the upper parts of the copper lodes, and the general similarity in the age and the conditions of occurrence of both types of ores, point to some genetic tie between them.

There appear to be transitional types in which both classes of ores are represented, as in the famous Anaconda vein, which, in the heart of the cupriferous area, carries silver ores in its upper part, argentiferous copper ore below, and in depth only copper ore.

While the copper ores frequently occur as metasomatic replacements of the ferromagnesian minerals of the fractured or crushed granite or quartz monzonite, the lodes are poor where they cross the quartz porphyry or the aplite, owing to the absence in these rocks of ferromagnesian minerals.

The silver lodes, on the other hand, show a development of sericitic mica in the granitic country-rock, in which the felspar has been kaolinized and the quartz corroded.

The silver veins contain argentiferous fahlerz, ruby silver, and other silver ores, with sulphides of lead, zinc, arsenic, and iron; native gold and silver, with secondary ores of lead and a little occasional copper, occur in the gossan, associated with quartz, fluorspar, and, rarely, barytes.

Silicate and carbonate of manganese appear to exist as original constituents of the lodes.   The outcrops of the lodes are black, and, unlike the lodes of copper, show a well-marked banding of the ores.

The silver ores of Nevada occur mainly in granite, which in the district of Reese River is penetrated by felsite and propylitized porphyrite.   At Tonopah, however, the mining area consists of Tertiary propylitized hornblende andesite, dacite, rhyolite, basalt and tuffs, in a region otherwise composed of Palæozoic rocks. In the Tonopah region the lodes occur in association with propylitized hornblende andesite, which is the oldest of the Tertiary eruptives.

The Nevada silver ores consist of stephanite, polybasite, red silver ores, and tetrahedrite, with a little blende, galena, iron pyrites, and chalcopyrite.   The principal vein-material is quartz, but this is accompanied by carbonates of manganese and lime and by adularia felspar.   Free gold occurs with the ores, and antimony is occasionally present in important quantity at Tonopah.   The gossans contain bromide and chloride of silver.

The alteration of the country-rock is mainly that of silicification and sericitization, together with impregnation by iron pyrites.

In the State of Colorado the silver ores do not carry much gold, but are of a similar type to those described

from the State of Nevada; but there is present some fluorspar and barytes. In the south of Colorado the deposits of Creede occur in Tertiary eruptives, while near Georgetown they are met with in granitic and gneissose rocks.

The recently discovered mining region of Cobalt in the vicinity of Lake Temiscamang (Temiscaminque), on the border of Ontario and Quebec, is a good illustration of the association of silver, cobalt, and nickel ores; these are in veins which vary from a knife-edge to a foot or so in width. These traverse slates and conglomerates of Lower Huronian age, but in the southern part of the region occur in diabase and gabbro of post-Middle Huronian age. The ores, which are probably of hydrothermal origin, consist of native silver, argentite, and pyrargyrite, with antimonide of silver and other minerals. The deposits are marked by an abundance of nickel and cobalt compounds, such as smaltite, millerite, niccolite, and chloanthite (with decomposition products, nickel and cobalt bloom). Compounds of bismuth, arsenic and manganese, also occur, while, in small quantities, are the commoner sulphides, blende, galena, pyrites, and chalcopyrite. The principal veinstone is calcite, with subordinate amounts of quartz. According to Messrs. Campbell and Knight, there is a distinct order of mineralization, as follows: First came arsenide of cobalt, followed by arsenide of nickel and small quantities of other ores. Subsequently there was a period of disturbance, resulting in brecciation of the vein materials, with the infiltration of calcite, and deposition of native silver; lastly, the formation of bismuth ores.

Argentiferous deposits similar to those of Cobalt

occur on the Ontario shore of Lake Superior in the Silver Islet district.

Here the veins exist principally in a gabbro intruded into the Algonkian (pre-Cambrian) slates. The principal ores are silver and its sulphides, with galena, blende, and fahlerz. Compounds of nickel and cobalt are important constituents, while the principal vein materials are calcite with some fluorspar, barytes, and a little quartz.

At Broken Hill, New South Wales, antimonial silver ores occur in a lode crossing the schists. The lode is rich where it intersects bands of amphibolite, but in the other rocks it is thin and poor. The ore consists of argentiferous fahlerz and other antimonial silver compounds. Cobalt glance is a characteristic accompaniment. The argentiferous copper sulphide, stromeyerite, exists as a secondary mineral, while horn and native silver, with ruby silver ores, sulphides of lead, copper, antimony, arsenic, cobalt and nickel, iodide and carbonates of silver are also present, accompanied by carbonates of iron and lime.

One of the most celebrated mining countries of the world is Mexico, where, in addition to abundant deposits of silver and gold, ores of copper, lead, and other metals, are worked.

The silver ores are found at many places in the length of country between Chihuahua in the north and Oajaca in the south. The strike of the lodes is parallel with the lines of upthrust and folding which have affected the rocks of the Sierra Madre.

The principal rocks of the area consist of mica schists and metamorphosed slates, with intrusive diorites ; and Mesozoic and Tertiary sandstones,

shales, and limestones. Crustal movements in Middle-Tertiary times raised and disturbed the rocks, and initiated a period of volcanic activity resulting in the intrusion of porphyrite and outpouring of pyroxene andesite in association with volcanic tuffs and breccias. These were followed by rhyolitic invasions, at the close of which episode the lodes were formed. There are still later outpourings of basalts and dacites, but these are in no way connected with the mineral deposits.

Generally speaking the ores, where not altered, consist of red-silver ores, polybasite, etc., accompanied in depth by fahlerz, and still lower down by zincblende, galena, iron pyrites, and some copper ores. In their deeper parts the lodes are not rich in silver, being richest in the upper parts, in the zone of secondary concentration.

The highest portion of the gossan contains native silver, oxide of manganese, etc., below which is a zone containing chloride, bromide, and iodide of silver. (This is the zone of *Metales Colorados*, and in it gold often occurs native, frequently associated with copper-staining.) At a greater depth the richest bunches of silver ores exist as secondarily deposited sulphides in association with other sulphides which lie above the primary vein materials (the zone of *Metales Negros*).

The lodes vary greatly in width and in character. The Veta Madre is one of the richest silver veins in the world, the ore occurring in shoots or bonanzas, of from a few feet to 120 feet in width. The lodes are occasionally brecciated, but generally the principal vein-infilling is quartz, which is sometimes purple, but often banded, chalcedonic, and associated with small amounts of calcite, carbonates of iron and manganese,

and fluorspar.   Native gold is commonly found in the quartz of the upper parts of the lodes.

The lodes are sometimes characterized by the presence of druses, or cavities, containing zeolites, such as apophyllite, while orthoclase also exists as a true vein-mineral.   The characteristic types of alteration of the andesitic rocks, where traversed by the lodes, are silicification, kaolinization, and propylitization.

Exceptionally, as in the State of San Luis Potosi, the ores occur in limestones as irregular metasomatic deposits connected with narrow fissures.   The ores consist of carbonates and arsenates of lead with native and horn silver.

The deposits of silver ore in Peru and in the neighbouring country of Bolivia belong to that type of deposit now being described.   In particular should be mentioned the deposits of Cerro de Pasco.   The lodes are of post-Jurassic age, and consist in depth of argentiferous grey copper ores, pyrites, galena, and quartz. The upper parts of the lodes are characterized by gossan, called locally the ' pacos ' or ' cascajados,' in which, like the ' colorados ' of Mexico, rich secondary ores of silver are found in quantity with a little gold.

In subordinate amounts there occur here and there arsenical compounds, zincblende, and manganous compounds with carbonates, etc.

The lodes are connected with dacite (quartz-andesite), and occur either in this rock or in the Tertiary sandstones, slates, and limestones.

The association of silver ores and cassiterite in Bolivia was referred to in dealing with the tin veins on p. 99.

At Cerro de Potosi the silver ores occur in bleached, kaolinized and pyritized slates, and rhyolites ; they con-

sist near surface of native and red-silver ores, and in depth of sulphides of copper, zinc, and lead, with smaller amounts of sulphides of tin and arsenic, and thus link the ores as a class with the sulphidic ores of pneumatolytic origin.

The deposits of Oruro consist of iron pyrites, sulphides of silver, antimony, and copper, with tin ore. Lead ore, containing microlites of tin oxide, is found in depth, with zincblende, arsenic, wolfram, quartz, and carbonate of iron, etc., so that the deposits constitute a mixed type. The district is formed of Palæozoic slates traversed by dacite (quartz andesite), with which the ores appear to be connected.

Various modifications of veins of this unusual type, in which sulphidic silver and lead compounds are associated with tinstone, occur in other parts of Bolivia, as at Colquiri, where chloride of silver is found with calcite and carbonate of manganese; also at Huayna Potosi, Chorolque, and other localities, where minerals such as tourmaline, topaz, and fluorspar, are occasionally observed.

North-east of Serena, Chili, in the mining district of which the San José is the principal mine, the veins are connected with intrusions of dacite. In addition to native silver and the chloride, sulphide, telluride, and amalgam of silver, there is argentiferous galena, polybasite and cupriferous silver sulphide, together with traces of bismuth, cobalt, and nickel ores. The vein stone is barytes, calcite and quartz. At Coquimbo the Upper Jurassic limestones and intrusive porphyries are connected with veins of similar nature.

Near Chanarcillo, forty-eight miles south of Copiapo (Chili), the veins traverse Jurassic limestones cut by in-

trusions of augite-porphyrite, in the vicinity of which there is a development of calc-silicates and an enrichment of the ores in the lode and country-rock ; the lodes vary from a few inches to 32 feet in width.

The original ores are mispickel, blende, and pyrites, which occur at a depth.   Above these come native silver and sulphide of silver, with ruby silver ores; but near the surface the ores contain chloride and bromide of silver, native silver, with carbonates of lime, iron, and copper ; barytes also occurs. Clay and limonite is the common gangue in the upper parts of the veins.

The veins of Caracoles, in the desert of Atacama, are of similar nature, and are connected with dykes of quartz- and augite- porphyry intrusive in Jurassic limestones and marls.   The lodes are always richest when in or near the porphyry.

The cobalt-silver ores of the Erzgebirge, in Saxony and Bohemia, are typical examples of this class of deposit.   They occur in the metamorphic rocks in the vicinity of the post-Carboniferous granites.   The three principal districts are those of Schneeberg, Schwarzenberg, Johanngeorgenstadt, and Joachimsthal ; Geyer and Annaberg ; and Marienberg.

In these regions the veins fall into four groups.   The two older groups comprise the tin veins and the pyritic lead and copper veins, while the two younger groups comprise the cobalt-silver, and iron and manganese, lodes.

In the Joachimsthal group there are two series of lodes, known respectively as the *Morgengänge* (striking east-north-east) and the *Mitternachtgänge* (striking generally about north and south).   The principal vein minerals are quartz, calcite, carbonate of iron, and magnesite; the lodes vary in width from a few inches

to 2 feet, or even 6 feet, and they occasionally show brecciation. The Mitternacht group appears to be the only one worth working for silver at any depth. The ores are those of cobalt, nickel, bismuth, arsenic, and uranium, while silver exists as ruby silver, native silver, and complex silver ores, such as polybasite, together with a series of rarer minerals. In smaller amounts there are sulphides of iron, lead, zinc, and copper. The older vein minerals are compounds of the first-mentioned metals and quartz, but the silver ores and carbonates belong to a later phase.

The lodes are intersected by nepheline basalts and basaltic tuff; when much decomposed, the rotten basalt is known as ' wacke.' The mineralization of the lodes does not appear to have been complete before the intrusion of these basaltic dykes, as they themselves are mineralized in places.

In the Annaberg region the deposits are similar, but there is in addition a considerable amount of barytes and fluorspar. The country-rock consists mainly of grey gneiss, which is traversed by dykes of microgranite and by late Tertiary basalt-dykes. The veins are subsequent to the intrusion of certain mica-traps, but are older than the basalts.

The lodes are numerous, and belong to two series, intersecting one another at right angles.

The mineral sequence appears to have been as follows:

1. Barytes with quartz and fluorspar.
2. Carbonate of iron, and ores of nickel, cobalt, and bismuth.
3. Calcite with uranium ores.
4. Rich ores of silver with native arsenic.
5. Decomposition products.

In the neighbourhood of Marienberg a number of intersecting veins contain native arsenic and silver, ores of silver, uranium, cobalt, nickel, lead, copper and iron pyrites, in association with carbonate of iron, barytes, fluorspar, and quartz. These veins cut through syenitic and dioritic rocks.

In Europe silver veins of the quartzose type occur in Saxony (Freiberg), Hungary (near Kaschau), Baden (Kinzig Valley, in the Black Forest), and in other countries.

In the Freiberg district the lodes occur in metamorphic, and plutonic intrusive, rocks, and consist of quartz with sulphides of silver, red silver ores, and native silver, together with argentiferous sulphide of iron; very rarely they carry sulphides of lead and zinc, the latter being covered with films of silver glance.

Thin sections of the siliceous veinstone show the silver minerals dispersed in small quantities throughout a granular mosaic of quartz.

Some of the ores are complex compounds, such as polybasite, freieslebenite, etc., which are often met with lining cavities.

Later infiltrations also occur, the minerals comprising carbonates of iron and manganese, with calcite, barytes, celestine, gypsum, and fluorspar, and sulphides of antimony, arsenic, and copper.

In the Kinzig Valley, Black Forest (Baden), a series of silver-ore veins of somewhat varying mineral composition and age exists in both the older and newer rocks of the district.

The newer rocks consist of Triassic and Permian sandstones, which unconformably overlie the gneiss, of which the principal part of the mineral area is com-

posed. Serpentine and amphibolite invade the gneiss in restricted areas, while on the south there are intrusions of granite and syenite. Numerous intrusive hypabyssal rocks, such as granophyre, are also met with.

The lodes occur principally in the older rocks, but are also found in the Bunter and Rothliegende sandstones.

The veins of the oldest vein-system in the district have quartz as the principal veinstone, and are similar in nature to those of the Freiberg region. Other vein minerals are carbonates of iron and lime, red silver ores, silver glance and native silver, iron pyrites, chalcopyrite, galena and sulphide of antimony; a little gold is also present.

The other series of silver lodes of the district are respectively characterized by calcite, argentiferous lead ore, barytic copper and lead ore, and cobalt-silver ore.

In the Frohnbachthal mineral-area, in the same region (Baden), quartz lodes in gneissose rocks contain argentiferous fahlerz, sulphide of lead, and a little copper, with carbonates of lime and magnesia. In a later phase of the mineral-history of the veins there was introduced, in addition to the foregoing, compounds of nickel and arsenic. Barytes and dolomite, with sulphides of lead, silver and antimony, constitute a third phase, and, finally, the youngest set of minerals comprises native silver, compounds of copper and silver, sulphides of zinc, iron, and antimony with fluorspar, etc.

Slight modifications of the above types are found in Nassau and in Alsace.

To the south of the Brocken Granite (Harz Mountains) and its metamorphic aureole, the mining dis-

trict of St. Andreasberg is situated in the Wiederschiefer (Lower Devonian). The rocks consist of slates with limestone bands and intrusive sheets of diabase.

The actual mineral-area is cut off sharply from the surrounding district by two large crush-zones or faults (the so-called ' Ruscheln ') which converge westwards, and enclose a wedge-shaped area 3 kilometres in length by 1 kilometre in width on the east (pp. 188, 189).

The lodes are simple fractures varying in width from an inch to 1½ feet. The principal vein mineral is well-crystallized calcite, which exists in two generations. In the older generation there occur arsenical and antimonial ores and sulphides with nickeliferous and cobaltiferous minerals. In addition there are zinc and lead sulphides with subordinate amounts of copper pyrites, iron pyrites, and pyrrhotite. Of somewhat later origin is fahlerz, which occurs with quartz, the latter replacing part of the calcite. After this come sulphides of copper, lead, and, sparingly, zinc with native silver and millerite. A fourth stage in the history is the conversion of silver to stephanite and other sulphides, and the formation of arsenides, antimonides and complex minerals. Finally, native silver occurs with realgar, calcspar and many zeolites; and secondary carbonates with hornsilver, cobalt bloom, malachite, etc. Among the minerals present in small quantity are axinite, epidote, garnet, and fluorspar.

The barytic silver ores of the Guadalajara district, in Central Spain, are somewhat similar to those of the district north of Almeria, in Andalusia (Southern Spain). In the former locality the lodes are in gneiss and mica schist, and consist of quartz, barytes, and carbonate of iron. Native silver with ruby and other silver ores, such

as hornsilver and silver bromide, are associated with sulphantimonides. In Andalusia the argentiferous lead and copper ores are accompanied by barytes, strontianite, and carbonate of iron. Secondary compounds, such as limonite, sulphides and arsenides of silver, with limonite and hornsilver, are present in the upper parts of the lodes. In Seville native silver and silver ores are associated with cobalt ores and carbonate of iron.

In the Grecian Archipelago, the islands of Milos, Pharos, Santorin, etc., have long been known as argentiferous lead-districts. In Milos the ore is barytic, and the stockworks are genetically connected with rhyolite. Pyrites, chalcopyrite, and zincblende, are common vein-minerals.

The silver veins of Kongsberg, lying on the southwest of Christiania (Norway), have received much attention from writers, on account of the occurrence of native silver in quantity.

The region consists of metamorphic rocks penetrated by diorite, olivine gabbro, and other basic plutonic rocks. The metamorphic rocks consist of pre-Cambrian mica, hornblende, chlorite, and quartz schists, some of which are garnetiferous. Grey gneiss is also found, and in one mine there is a thin vein of diabase porphyrite. Some of the schists are impregnated with pyrites and pyrrhotite along certain zones or bands, which at surface weather a yellowish-brown. These zones are known as 'fahlbands' (grey bands). There are six of these impregnated zones, which vary irregularly up to several hundred yards in width.

The pyritic bands occur principally in the mica schist, being scarce in the hornblende-schist, and barely represented in the gneiss. Among other minerals present in

in the fahlbands are sulphides of copper, and cobalt and silver ores, in exceedingly small quantities. The lodes, of which there are a great number, often close together and forming a network, vary from a mere knife-edge to 2 feet in width, and traverse the fahlbands obliquely in a north-westerly direction. Only those parts of the lodes which traverse the fahlbands are rich enough for mining. The vein-minerals are calcium carbonate, fluorspar and quartz. Dolomite and barytes are rare. Adularia and albite also occur with asbestos and asbestiform minerals. Carbonaceous minerals, such as anthracite and graphite, are occasionally met with in quantity. Zeolites, such as apophyllite, harmotome, stilbite, etc., are also found, and sometimes prehnite is present.

The principal ores are native silver in various forms associated with calcite, but quicksilver and gold also exist with mercurial compounds, hornsilver, red silver ores, and complex compounds of iron, cobalt, arsenic, antimony, copper, silver, and sulphur. Among the other metalliferous minerals we may mention marcasite and other sulphides, such as those of zinc, copper, lead, arsenic, and iron, all of which are more or less argentiferous. Pyrrhotite is also present, and there is a rarer occurrence of native arsenic and copper with cobalt bloom and carbonate of iron. As a whole, it should be remarked that the native silver is by far the most important mineral, and in comparison with its sulphides occurs in the ratio of anything from 10 to 20 to 1.

The reactions which brought about the formation of native silver are supposed to have been initiated by the action of steam on sulphides and sulpharsenides of silver, and to have produced native silver, native

arsenic, etc., and a liberation of sulphuretted hydrogen and sulphur dioxide (see p. 361). It has been stated that the silver was originally brought to its present position in solution as the carbonate or bicarbonate of silver, which was decomposed by carbonaceous matter or ferrous compounds. It has also been shown experimentally that a hot solution of ferric sulphate dissolves silver, but this action is reversed at lower temperatures, as expressed in the following equation:

$$2Ag + Fe_2(SO_4)_3 \rightleftharpoons Ag_2SO_4 + 2FeSO_4.$$
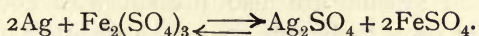
Veins similarly connected with fahlbands have been worked in Dauphiné, France. The Hungarian silver ore deposits, near Kaschau, were formerly worked for gold in the upper parts of the lodes, where it occurred with antimony ochre. The primary ores consist of argentiferous antimonite, jamesonite, etc.; and slightly auriferous pyrites, sulphides of zinc, copper, and arsenic, with quartz, a little calcite, and carbonate of iron.

The silver ores of Japan (Akita, island of Sado, and near Tokyo) belong to the siliceous sulphidic group. They are connected with Tertiary eruptives, the intermediate types of which are propylitized. In some localities compounds of manganese occur in abundance, but in others cupriferous minerals enter largely into the composition of the lodes. In addition to quartz, calcite and other carbonates occur with sulphides of silver, lead, zinc, and iron. Gold is of importance in some of the veins.

In the province of Chi-li (China), ruby silver ores, argentite, and chloride of silver, are found in association with galena, blende, and arsenical ores which are connected with dykes of felsite.

The silver ores of Southern Sardinia occur in a granite and in the zone of metamorphosed Silurian rocks into which it is intruded. Near the surface the lodes consist mainly of barytes and galena with quartz, calcite, and zincblende. In depth they are siliceous, but consist largely of calcite with fluorspar and zeolites; the metalliferous minerals usually comprise native silver, argentiferous galena and blende, hornsilver, and ruby silver ores; marcasite, pyrrhotite, and sulphides of copper and arsenic are also present with cobalt and antimonial ores, carbonate of iron, and other minerals. The final phase of lode formation is represented by carbonate, phosphate, and chromate of lead, with nickel and cobalt bloom, etc.

VEINS OF NICKEL AND COBALT ORES.

The ores of nickel and cobalt are divisible into two main groups; the first of which includes the sulphides of cobalt, nickel, and bismuth; the second, however, comprises the hydrosilicate ores of nickel, which belong to the oxidic hydatogenetic types of veins, and which are described under that head. The second group is the more important commercially.

In the sulphidic nickel and cobalt group the ores are further subdivided into two more or less indefinite types, according to the dominant mineral constituents.

The ores of nickel and cobalt occur principally as sulphides or arsenides, and comprise such minerals as smaltine, cobalt glance—double sulphide of nickel and cobalt, erythrine, asbolane (wad with oxide of cobalt up to 40 per cent.), chloanthite, millerite and various sulphates, arsenates, arsenides, and antimonides

of nickel. Many of these exist as accessory minerals in lodes of other ores.

Millerite has been found in nodular concretions of carbonate of iron in Carboniferous Limestones of St. Louis, where it occurs with magnesium and calcium carbonates, gypsum, fluorspar, strontianite, barytes, and pyrites. On the whole, it is of quite subordinate importance among the nickel ores.

The minerals which are associated with the sulphidic cobalt - nickel ores are compounds of bismuth, silver, copper, and arsenic in a gangue of quartz, calcite, carbonate of iron, barytes, and fluorspar. According to the dominant minerals present, the veins fall into the following two subgroups:

1. Cobalt-nickel ores with carbonate veinstone further characterized by the presence of quartz barytes, fluorspar, silver, and copper.

2. Cobalt-nickel-bismuth-silver-quartz ores.

Typical Examples of Nickel and Cobalt Veins.— The deposits of Temiscamang, Ontario, have been described under silver ores (p. 201).

At Dobschau, in Hungary, veins and strings contain carbonate of iron; copper, nickel, and cobalt ores; a little quartz and various sulphides, with ankerite, tourmaline, calcite, and rarely barytes. They are connected with a laccolitic intrusion of diorite in epidotic and chloritic clay-states and calcareous schists derived from hornblende-felspar rocks. These are overlain by Carboniferous limestones, in which the veins are also found, and which are in part metasomatically replaced by carbonate of iron from the lodes.

Niccolite, with carbonates such as calcite, ankerite, and spathic iron ore, also copper ores and barytes, are

found in faults or lodes traversing the Mansfeld copper-district, in the Thüringer Wald.

At Kamsdorf and other places in Thuringia (Saxony), lodes, occasionally brecciated, and traversing both the Kupferschiefer and the underlying conglomerate of the Zechstein series, contain asbolane, cobalt bloom, and smaltite, with calcite and barytes. The cobalt lodes of Spessart, near Baden, have a similar genesis.

In Styria, the hornblendic slates and gneiss contain wide pyritic zones, or fahlbands, in which mispickel, pyrrhotite, and iron pyrites, form band-like masses. Near the surface the sulphides are oxidized. The cobalt and nickel ores are found in lodes traversing these fahlbands, and are associated with calcite, quartz, and the ores of lead, bismuth, arsensic, and copper.

In the Fichtelgebirge, the ores of cobalt and nickel are found with carbonate of iron, bismuth, and barytes; while in the district of Siegen, Prussia, they are met with in lodes containing carbonate of iron and copper ores.

In the Schneeberg district, already referred to under silver ores (p. 206), the cobalt-lodes are connected with the granites which are intruded into schists and contact-altered slates; they are younger than the tin lodes.

The cobalt-lodes are numerous, and the ores are characterized by quartz, and nickel and bismuth ores; they are met with among decomposed crushed country-rock which fills the veins. Calcite, carbonate of iron, and ankerite, with occasional barytes, fluorspar, and ores of arsenic, silver, uranium, copper, zinc, and lead, are met with. At the time of formation of the lodes, the original minerals appear to have been mainly carbonates with barytes; these have been subsequently replaced by silica.

In the Wallis Valley district, situated between the Pennine Alps and the Bernese Oberland, lodes of copper, in chloritic gneiss, contain cobalt and nickel ores with spathic veinstones; they are characterized by the presence of quartz, copper sulphide, grey copper ore, galena, lead molybdate and other secondary ores of lead.

Cobalt and nickel ores occur in Piedmont, with quartz, calcite, and ores of copper.

In Nassau, lodes of quartz with spathic iron ore, ankerite, copper and nickeliferous pyrites, and bismuth ore, are found in ancient volcanic tuffs and picrites.

In Los Angelos County (California), argentiferous cobalt ores are found in lodes having a barytic vein-stone.

The occurrence of cobalt and arsenical ores with gold and silver in quartz lodes which traverse talcose slates has been noted in connection with acid intrusions in Sierra Famatina, Argentine.

Cobalt ores are found in lodes traversing schists near Balmoral (Transvaal). Here the lodes consist of chalcedonic quartz and fibrous hornblende with smaltite, cobalt bloom, and molybdena.

BISMUTH ORES.

The most common bismuth-minerals are the native metal and its sulphides. Among the subordinate ores may be mentioned compounds of bismuth with selenium, tellurium, silver, gold, copper, and lead ; while oxides, carbonates, arsenates, and silicates, are also known in still smaller amounts as secondary products.

There is no well-marked group of bismuth veins, and in the natural classification minerals of bismuth must be regarded, not as the principal, but as subordinate

constituents, occurring occasionally in such quantities as to establish exceptional modifications of other veins.

Thus, they sometimes occur in appreciable quantities in auriferous quartz veins, as in the auriferous bismuth ores, pyrites, and mispickel, of Queensland; they are probably connected with granite, and in New South Wales, quartz, with native bismuth, gold, and molybdenum, occurs near the contact of granite with slates.

The most important deposits of bismuth are those of Bolivia (Chorolque and Tasna), where they are met with in a large number of veins which have close affinities with stanniferous-silver veins. The ores consist largely of bismuth intergrown with cassiterite, and seem to be connected with dykes of dacite and quartz trachyte traversing altered clay slates; wolfram also occurs. In association with the ores are the usual accompaniments of the silver-tin lodes, such as pyrites and other ores of iron, sulphides of copper, lead, zinc, etc., with quartz, siderite, barytes, and occasionally tourmaline.

Bismuth ores occur also in Telemarken in association with tourmaline-copper veins containing sulphides of iron and lead with quartz and carbonates; in many tin-fields, as in the Altenberg, in some parts of Cornwall (East Pool Mine), and in Queensland.

In association with copper sulphide, bismuth ore occurs in the Cobar Mine in New South Wales. In Australia bismuth has been noted as occurring in an ochreous deposit round a thermal spring; the minerals present were gold and bismuth carbonate, but on being followed downwards the deposit was found to contain the telluride of bismuth.

ANTIMONY ORES.

The ores of antimony, like those of bismuth, most frequently occur as abnormal developments of lodes which principally contain other metals ; but in some regions they occur as the principal lode-minerals, and were generally deposited as the sulphide or native metal from alkaline solutions. Oxides, together with more complex ores, such as bournonite, jamesonite, antimonial fahlerz, and numerous other antimonial ores, are also found. Exceptionally the amorphous sulphide is met with, as at Steamboat Springs, Nevada, where it has been deposited on sinter.

The principal vein accompaniment is quartz, but subordinate amounts of brownspar (ankerite), calcite, and barytes, may be present, with sulphides of lead, zinc, iron, and copper ; in one type of vein the ore is accompanied by a high gold-content, and is therefore described with the gold ores. Transition types to cinnabar and to realgar veins are also known, as at Huancavelica (Peru). In Tuscany, also, deposits of cinnabar and realgar are connected with antimonial ores. In the decomposition of the antimony sulphide to antimony ochre, sulphur reacts on limestone, with formation of alunite and gypsum, which are often characteristic of the upper parts of the lodes.

Some hundreds of tons of antimonite, antimony ochre, jamesonite, and other ores of lead and antimony, have been raised from lodes in North Cornwall, where the ore is principally accompanied by quartz. Bournonite and antimonite were common accompaniments of the lead ores in Herodsfoot and other mines near Liskeard (East Cornwall), where the lodes were further

characterized by the presence of quartz, fluorspar, calcite, and chalybite.

In York County, New Brunswick, ores of native antimony and stibnite, containing a low percentage of gold and silver, are found in association with calcite and quartz in veins traversing black slates. In Sonora County, Mexico, important deposits of antimonial oxides are found (p. 292).

In New South Wales and Victoria, antimonial ores have been mined. In New South Wales they are associated with quartz, while in Victoria (as at Sunbury) the antimony is found in gold quartz.

Of European localities for antimony those of Westphalia, Saxony, and Bohemia are the most noted.

In the Unterharz, the sulphide of antimony occurs with various metallic sulphides and arsenides, calcite, strontianite, ankerite, siderite, barytes, gypsum, fluorspar, and quartz, in breccias in Palæozoic slates.

At Mileschau, in Bohemia, veins containing antimony as radiating needles are found in connection with kersantite which traverses hornblende-granite.

In Oporto (Portugal) antimony in association with gold is found in a district containing, in addition to tin and wolfram veins, lodes of argentiferous galena.

In France the departments of Cantal, Haute-Loire, and Puy-de-Dome yield antimony ores, the lodes of which occur in gneiss, mica-schist, and granite. The veins consist of antimonial ores with quartz and a little zincblende and pyrites. Argentiferous and plumbiferous veins with antimony also occur, while calcite and barytes are occasionally present as gangue minerals.

Antimonial ores are also worked in Corsica and Sardinia. In Corsica the antimonial ores are complex,

and consist of quartz with various sulphides, including cinnabar, native sulphur, and calcite. In Sardinia also the veins contain calcite.

The Tuscan antimony lodes contain sulphides of arsenic and mercury with quartz, and occasionally sulphur in pockets and stringers. Between the Permian shales and the Eocene limestones are siliceous ore-bodies which yield antimonial ores.

In Hungary the antimony lodes consist of quartz and calcite, with stibnite and pyrites. The ores are particularly rich where the lodes are in graphite or chlorite schists, and the latter become impregnated with sulphide of antimony, pyrites, and a little cinnabar, for a distance of 12 feet on either side of the lodes. Lodes containing antimonial ores with blende, auriferous pyrites, quartz, and calcite, are also known.

Oxides of antimony occur in limestone of Neocomian age in the province of Constantine, Algeria.

In Japan, K. Yamada has described antimonial ores in the island of Shikoku, where lodes occur in sericitic schists, which near the lodes are impregnated with pyrites. The veinstone is quartz with some calcite.

In Sarawak, Northern Borneo, antimonial ores are found in lodes traversing limestones and slate. The ores consist of stibnite, native antimony and oxide of antimony, in quartz.

ARSENICAL ORES.

The principal arsenical minerals are realgar and orpiment. Arsenic is, however, a very common associate of antimony, and occurs united with it in the complex ores of other metals, such as fahlerz, etc.

Native arsenic is also found with native antimony.

The occurrences of workable deposits of arsenical and antimonial ores are limited, but are known at Alchar, near Salonica (Turkey), in New Caledonia, and other places. In comparison with the numerous antimonial veins, those containing similar compounds of arsenic are quite rare.

Realgar and orpiment are deposited from some hot springs, and as sublimates are connected with volcanic activity. They are also met with in veins and as impregnations.

In Galicia realgar occurs with gypsum and quartz in argillaceous rocks, in Tuscany in marl, intergrown with gypsum and marcasite, and associated with sulphide of copper, pyrrhotite, limonite, sulphur, and fluorspar. In the same province it is connected with cinnabar, as has also been observed in Asturias (Spain) and at Huancavelica (Peru).

Near Civita Vecchia veins traversing sandstones contain calcite, realgar, and orpiment.

Near Kremnitz, in the Hungarian ore-mountains, Triassic dolomitic limestones are traversed by irregular veins containing clay, in which are embedded lumps of arsenic sulphide; it is also found in pockets at the upper limit of the limestones.

While the arsenic veins seem to fall into a group of their own, they do not constitute the main sources of arsenic.

The most important sources are those in which the arsenic is a by-product of the working of other veins. The principal ore is the double sulphide of iron and arsenic (mispickel or arsenical pyrites); in silver and lead veins it occurs at St. Andreasberg, Pribram, and other places, and in the barytic silver veins of Saxony.

The presence of arsenical pyrites in very large quantities in some of the largest tin and copper mines of the West of England—as near Tavistock and in the Camborne district—is remarkable, more particularly as the lodes belong to the pneumatolytic group. Antimony is only rarely present, and cinnabar is absent. Under similar circumstances this ore is found in the tin mines of Saxony and Bohemia.

QUICKSILVER ORES.

The principal natural compounds of mercury are cinnabar (red sulphide) and metacinnabar (black sulphide), which have the same chemical composition. The metal also occurs native, and rarely combined with chlorine, tellurium, and selenium; mercury as sulphide is also contained in quicksilver-fahlerz, as in Bosnia, Hungary, and Chili.

The ores occur in rocks of all kinds and all ages, but generally in zones of fracture, fissures, breccias, and openings, with the formation of stockworks and lodes. They are also found as impregnations of sandstones. The deposition of the ore has sometimes been accompanied by silicification of the country-rock, but as a rule it takes place without metasomatic mineralization. A number of deposits are connected with limestone in which the mercury sulphide is generally found as most irregular masses embedded in clay; it is doubtful whether these deposits should not be classed with those of metasomatic origin. The form of the deposit and its commercial importance naturally vary according to the rocks in which the deposits are found.

Cinnabar may be accompanied by other minerals, such as copper pyrites, mispickel, marcasite, stibnite,

and realgar ; it is sporadic in many sulphidic veins which carry gold, silver, and the sulphides of copper, lead, and zinc; the accompanying veinstones are quartz, chalcedony, opal, bitumen, calcite, dolomite, brown spar, and, more rarely, barytes, fluorspar, gypsum, and sulphur.

Antimony, as a mineral paragenetic with mercury, occurs in California, Mexico, Borneo, Russia (Nikitovka), Corsica, Servia, Bosnia, and Hungary. A mineral having the composition $HgSb_4S_7$, is found in Mexico, and in Hungary cinnabar has, in some instances, been deposited on antimonite. An abundance of iron pyrites in some places is an indication of the presence of mercury.

Mercury is freely soluble in hot strong sulphohydrate or carbonate solutions forming a double salt with one of the alkalies—as, for instance, $HgS4Na_2S$; from this it may be precipitated, as a sulphide with a little free mercury, by dilution, or by the action of some bituminous matter with which it is so frequently associated, as at Idria, in California, and in Russia.

As sodium sulphide also dissolves pyrites, blende, gold, etc., these minerals are found with cinnabar. When such solutions react on limestone, the limestone is converted partly to gypsum and partly to more soluble compounds, while any argillaceous material which may have been present is impregnated with cinnabar and left in the place of the limestone. Carbonaceous or bituminous material favours the deposition of cinnabar.

The deposits appear to have originated mainly by the deposition of cinnabar from such solutions as these, but, owing to the volatility of mercury and

mercurial compounds at comparatively low temperatures, some think that they may be due to sublimation; it is highly probable that steam was an important factor in many cases.

The dark sulphide—metacinnabar—occurs as an alteration of the red cinnabar, and is frequently present in the upper parts of such deposits. Native mercury may result from oxidation of the sulphide.

In the deposits of Almaden, the cinnabar occurs impregnating sandstone, from which much of the siliceous material appears to have been dissolved.

Deposits of mercury are found in connection with the following igneous rocks: Granite (Corsica); diabase (Almaden); in greenstone-porphyry, melaphyre, and basalt; serpentine and olivine rock (California); rhyolite (New Almaden); trachyte and other lavas.

Typical Examples of Quicksilver Deposits.—The most important deposits of mercury are those of Almaden, in the Sierra Morena (Southern Spain). The rocks consist of highly inclined Silurian and Devonian shales, and quartzites, broken through by diabase and melaphyre intrusions.

The cinnabar occurs in three beds of quartzite as more or less complete impregnations, or as strings running through the beds. The impregnations die out gradually in the quartzites, but suddenly where these abut against the shales.

The cinnabar is associated with native mercury, pyrites, and copper pyrites. Other minerals are practically non-existant, but a little barytes is present with some bituminous material.

Very little mercury occurs in the shales and limestone, while none is found in the igneous rocks.

In the province of Asturias, cinnabar, with arsenical ores containing up to 0·7 per cent. of mercury, occurs in breccias, and as impregnations of quartzites and conglomerates in a Carboniferous limestone-series.

The celebrated quicksilver deposits of Idria, in Carniola (Austria), occur in a series of Triassic limestones, shales, tuffaceous sandstones, marls, dolomites, and conglomerates.

The cinnabar exists as impregnations of dolomite and dolomitic breccias in association with pyrites and native mercury, with minerals such as quartz, secondary calcite, dolomite, some fluor, and an appreciable amount of bitumen, which has probably acted as a precipitant. The richest of the mercury deposits occupied fissures in connection with the bodies of ore, but they have all been worked away.

There are two groups of mines in the region. Those of the south-eastern district are working on lodes about 3 feet wide, situated in dolomitic breccias and conglomerates, which lie between dolomitic beds above, and calcareous slate and marly limestone, below. The cinnabar impregnates the overlying dolomites for considerable distances, and also passes along the less important but parallel zones of brecciation.

In the north-west mine the rocks are much folded. The rocks overlying the conglomerate are highly bituminous shales impregnated with ore in the form of irregular bunches and pockets, ranging up to 60 feet or more in width, and traversed by numerous veins. The process of impregnation probably took place in Eocene times.

The cinnabar deposits of the old volcanic regions of Tuscany occur in zones of excessive fissuring in the

Upper Liassic clays and limestones. The clay is a residue from the limestones, the lime of which has been dissolved away by the solutions which brought in the cinnabar and associated pyrites. Gypsum also occurs. In the formation of these deposits, it seems that the solutions contained mercury and sulphates of other metals, with sulphuretted hydrogen; the final result was the formation of alkaline sulphides, which precipitated cinnabar from solutions; these were neutralized by reactions with limestone. Other ores, in the siliceous Liassic rocks below, appear to be secondary, and to have been concentrated by solutions containing carbonates.

In other places in Tuscany the mercury ores occur in Eocene bituminized limestones (nummulitic) and clays, and in trachyte. Cinnabar is found in strings with iron pyrites (marcasite) and opal in trachyte.

The Servian deposits of cinnabar occur in an enormously wide siliceous lode, over 200 feet thick, which is itself traversed by barytic quartz veins with cinnabar, some native mercury, and calomel. The lode is in a serpentine which has been intruded into Cretaceous limestones.

The cinnabar of Nikitovka, near the Donetz River, is met with in fault-fissures traversing carbonaceous sandstones, quartzites, and seams of coal, and is associated with stibnite and pyrites.

The deposits in the eastern part of the Saarbrucken coalfield, in the Rhenish Palatinate, consist of numerous fissures and impregnations in Carboniferous sandstone, clay slate, and melaphyre, also in melaphyre-conglomerate, and quartz porphyry. The ores are found in small streaks and druses in clay, with native mercury, calomel,

and other minerals, of which pyrites, galena, copper pyrites, stibnite, silver, quartz, barytes, and bitumen, are the most important.

The Californian quicksilver deposits of Sulphur Bank, New Almaden, New Idria, and Great Western mining districts are situated in the coastal mountains, which consist of folded Cretaceous slates pierced by intrusions of granite, quartz porphyry, andesites, rhyolites and basaltic rocks; the mercurial ores are most often associated with andesite and basalt. The deposits as a rule consist of irregular lodes of cinnabar, with numerous small veins and stockworks or impregnations of the porous country-rock, but there is no extensive metasomatic replacement.

At the Great Western Mine the cinnabar is in association with pyrites, quartz, and bitumen, in a flat deposit at the junction of Neocomian sandstone with an opalized serpentine.

The New Almaden ores of cinnabar and native quicksilver occur as stockworks in the vicinity of disturbed sandstones, serpentines, and diabase. Associated with them are copper and iron pyrites in small quantities, also quartz, calcite, dolomite, and magnesite.

In Brewster County, Texas, the ores are found in Cretaceous shales and limestones, which are traversed by sheets, dykes, plugs, and laccolites, of rhyolite and phonolite, and covered by lava-flows of a basaltic character. The limestone is of Lower Cretaceous age, and is represented in the Terligua District. Here the limestone is somewhat cavernous, and is traversed by veins and strings of calcite, which contain cinnabar, together with gypsum and the oxychlorides of quicksilver. In some cases the walls of cavities are lined

with cinnabar, which is also met with in quantity on the floors of such caverns. Friction-breccias cemented by calcite and gypsum, with oxidized pyrites and cinnabar, are not uncommon features.

Cinnabar is also met with in the shales of the Upper Cretaceous. In the Study Butte region the shales contain thin bands of limestone, and the whole is situated between beds of sandstone. The quicksilver ores are also found traversing the igneous rocks in the form of strings.

The Peruvian deposits at Huancavelica occur in slates, limestones, sandstones, and conglomerates, of Jurassic age, penetrated by trachytic rocks, with which they appear to be connected. The accompanying minerals are pyrites, mispickel, and sulphide of arsenic.

At Huitzuco, in the State of Guerrero in Mexico, the mercurial ores consist of cinnabar, metacinnabar, livingstonite, pyrites, gypsum, sulphur, calcite, and bitumen. The occurrence of the antimonial sulphide of mercury, livingstonite, is the most remarkable feature.

In the State of San Luis Potosi, the cinnabar of Guadalcazar is connected with massive limestones intruded by granite and porphyry. Unimportant deposits of zinc and lead are also found. The cinnabar is in the disturbed limestone, and in irregular deposits in clay, with calcite, fluorspar, gypsum, and a little barytes.

In the State of Santa Rosa, Mexico, cinnabar is found in dolomitic limestone, passing into white limestone, in association with free mercury, quartz, and clay.

In China, cinnabar deposits associated with antimony, occur in the province of Kweichou, in quartzose veins traversing dense magnesian limestone. The deposits are found to be of several forms: (1) As impregnations

in well-defined beds; (2) as impregnations along joints and bedding planes; (3) as isolated masses, pockets, and vugs, containing cinnabar, calcite, and quartz; (4) irregular disseminations in a number of disturbed limestone beds.

Oxidic Veins of Hydatogenetic Origin.

This class of veins comprises ores which consist mainly of oxides, carbonates, and silicates, which have been deposited from solutions. Although not infrequently accompanied by sulphides, such compounds are generally only present as accessory or accidental minerals, except in the veins which are intermediate between the true oxidic veins and those carrying sulphidic ores with large amounts of carbonates.

The most important minerals of this group are the oxides and carbonates of iron and manganese, but the hydrosilicates of nickel are also included. With regard to the source of the ores of iron and manganese, there is much uncertainty, but in the case of the nickel the connection with serpentine is undoubted. There is a total absence of minerals formed under pneumatolytic conditions.

OXIDIC ORES OF IRON AND MANGANESE.

Iron and manganese ores have a similar mode of occurrence in Nature, are not uncommonly associated with one another, and have similar veinstone accompaniments.

The common ores of iron are red and brown hæmatite and the spathic iron ore. The brown hæmatite (limonite, etc.) generally arises from a secondary alteration or hydration of red hæmatite or of spathic iron

ore, so that it is found in the upper parts of veins carrying either of these minerals.

In the lodes of spathic iron ores the principal material is carbonate of iron (siderite or chalybite), with quartz, carbonate of lime, and accessory sulphides of iron and copper, with barytes. As a rule, oxides of manganese are met with in the upper parts of spathic iron lodes, and have been liberated during the oxidation of the carbonate, as in some of the Cornish lodes. Brown hæmatite also occurs as a secondary mineral in the gossan.

In Cornwall, for instance, the Great Perran iron lode is composed largely of carbonates, which near the surface are oxidized to limonite. Similar lodes occur in Devonshire and Somerset.

The iron ores of the North of England are generally either bedded deposits or metasomatic replacements, so that they will not be dealt with here; but it should be observed that some of the lead veins of the Alston district (Northumberland) are characterized by large amounts of spathic iron ore, which, however, are of small economic importance, in view of more abundant and purer deposits elsewhere. Hæmatite has been worked in lodes in the Skiddaw Slates and in granite in Cumberland.

Some of the iron ore deposits on the Continent, as in the Rhineland, are of this type, and consist of slightly siliceous spathic iron ore with a large percentage of manganese. A little copper ore, zincblende, and galena is present, giving these veins a character intermediate between the true spathic iron veins and the copper veins characterized by carbonates.

In the Hungarian ore-mountains, in the Zips (Szepes),

lodes of spathic iron ore have been worked with copper ores, barytes, and occasionally a little cinnabar.

Spathic iron ores have also been worked in Connecticut (U.S.A.), where, in addition to spathic ores, sulphides of various metals occur with quartz.

In the red hæmatite ores the principal veinstone accompaniment is quartz or jasper, with small amounts of carbonates of lime and iron, limonite, a little barytes, manganese, and fluorspar. These deposits may be regarded as modifications of spathic iron veins.

In Saxony the red and brown iron ores, in the district near Zwickau, consist of red and brown hæmatite with ferruginous quartz; they exist either as contact deposits between greenstone and slates, or as irregular siliceous impregnations of Ordovician quartzites, or as pockets and ramifying veins in masses of Ordovician diabases. They are believed to have been formed by lateral secretion, and possibly by decomposition of the diabase.

In the Erzgebirge of Saxony, the veins occur in brecciated lodes in both granite and metamorphic rocks, and contain hæmatite and limonite, with small amounts of bismuth and cobalt ores and sulphide of copper, wavellite, fluorspar, carbonates of lime and iron, barytes, quartz, jasper, chalcedony, clay, etc. Manganese ores sometimes exist in considerable quantity; they are always among the later minerals of the lodes, for they are found to traverse them in strings; but occasionally they occupy the whole width of the lode. Calc- and copper-uranite are also found.

The manganese lodes contain ores of manganese, in association with veinstone materials similar to those characterizing the iron lodes, the principal being quartz,

calcite, and barytes. Like iron ores it is necessary, for commercial purposes, that the manganese ores should contain over 40 per cent. of the metal, and the number of deposits of this type containing ore rich enough for working is somewhat limited. The ores principally used are secondarily enriched bodies ; nine-tenths of the material wrought being used in the manufacture of *spiegeleisen* and manganese steel, while the rest is employed in the preparation of chlorine, permaganate of potash, and other substances of commercial value.

The German manganese lodes have received considerable attention from Continental geologists. At Langenberg, in Saxony, there are large brecciated lodes and stockworks, which at their outcrops are connected with secondary deposits which occupy shallow, basin-like depressions in schists, and consist of iron and manganese ores. In some localities, as at Graul, similar deposits contain cobalt and manganese ores, with bismuth-ochre.

In the Eibenstock granite, and near Platten, in Bohemia, the manganese ores form stockworks, and veins ranging up to 3 feet in width. At Johanngeorgenstadt (Saxony), the ores occur as bedded veins in schists and slates, the country-rock being impregnated with soft ores of iron. Pseudomorphs of hæmatite after calcite, anhydrite, and pyrolusite, are found. The manganese is mainly in the form of oxides.

In the Harz Mountains, at Ilfeld, deposits of manganite, psilomelane, braunite, hausmannite, pyrolusite, and wad, in association with barytes and carbonates of iron, magnesium and lime, are found in thin strings and veins in a mass of weathered porphyrite which is intrusive in the Rotliegende (Lower Permian).

In the Thuringerwald, veins of manganese ores traverse porphyry, melaphyre, and melaphyre conglomerate.

In Styria (Veitsch), the lodes traverse Silurian lime-stones, and consist of rhodochrosite.

In the department of Saône-et-Loire (France), lodes of psilomelane with quartz, barytes, fluorspar, limonite, and hydrated oxide of arsenic, are connected with granite. The lodes are formed along lines of over-thrusting traversing Tertiary rocks.

In the district of Huelva, and in a zone of the Silurian slates extending from Seville to Cape Sineo, on the Portuguese coast, are found lenticular masses of silicates of manganese, iron, and lime, which have had their origin in thermal springs. In association with them there are quartz (frequently jasperoid), carbonate of manganese, and pyrites. In depth the deposits are more pyritic, and it is only the dark weathered outcrop which is worked. At Santa Catalina, however, the ores have been mined to a depth of 330 feet.

HYDROSILICATE NICKEL ORES.

These nickel ores are connected with the serpentiniza-tion of peridotite and pyroxenite rocks; they may be regarded as having been deposited in the fissures tra-versing masses of serpentine by the combined processes of lateral secretion and hydatogenesis, acting during the change of olivine-bearing rocks to serpentine, and of a subsequent concentration by weathering of the ser-pentine. Some of the ore deposits may possibly be regarded as allied to segregations (see pp. 69, 70).

The nickel probably occurred in minute quantities in the ferromagnesian silicates of the original peridotites, which shortly after intrusion became changed to ser-

pentine. In the further alteration of the serpentine the nickel ores were concentrated in fissures as genthite and garnierite, while clay with quartz, chalcedony, opal, chrysoprase, gymnite, and asbestos, were also deposited. On the decomposition of the ferromagnesian minerals, some of the magnesia and silica was carried off into fissures, while ferruginous residues, containing nickel ores, were left in pockets. Carbonates are absent. Whether these changes were effected by springs or by ordinary weathering action is uncertain. The veins in the serpentine are very numerous, and much of the ore is brecciated.

In New Caledonia, the nickel ores, garnierite (from their discoverer, Garnier) and noumeaite (after the town of Noumea) occur, both in serpentine and at its junction with adjacent clays, in the form of strings, veins and stockworks. The clays themselves contain ores of iron, cobalt, and chromiun, but no nickel. The rest of the country consists of Archæan rocks. The ores extracted contain from 4 per cent. to 4·5 per cent. of metallic nickel. Cobaltiferous manganese ores also occur in the island.

The deposits of Revda, south-west of Ekaterinburg, in the Urals, are connected with antigorite serpentine, which occurs in schists and metamorphic limestones. The nickel-magnesium silicates exist in the form of brecciated material cemented by quartz and chrysoprase, in ferruginous decomposition products of the serpentine.

In Webster County (North Carolina), the deposits of nickel are connected with the change of dunite to serpentine. The olivine of the original rock contains nickel. The nickel ore, genthite, occurs in small fissures with talc and gymnite, but no quartz.

The post-Cretaceous intrusions of harzburgite near Riddles (Oregon) are connected with nickeliferous veins. The rock has been to some extent serpentinized, but contained originally olivine and bronzite with chromite and magnetite. Serpentine veins traverse the mass, in association with hydrous silicate of nickel. At the time of the separation of the nickel ore, numerous veins of quartz and iron oxide resulted from the expansion which accompanied the chemical changes in the rock; they consequently often radiate from centres.

In Silesia the deposits of nickel ore are connected with serpentine, formed from peridotite, in which the remains of olivine crystals occur, together with magnetite, tremolite, and chromite.

The veins in this half-serpentinized rock consist of serpentine, talc, and clay, and are themselves traversed by narrow veins of garnierite and other nickel ores in association with quartz, opal, and chrysoprase.

The so-called 'nodular ores' are found in pockets and stockworks.

CHAPTER V

ORES DUE TO METASOMATIC REPLACEMENT

By 'metasomasis' is meant a chemical process involving the replacement of one substance by another, not necessarily with the retention of the form, or even volume, of the original mineral. For instance, should a pure limestone be converted into a dolomite by the replacement of part of its calcium by magnesium, such a change would be purely chemical, and would be known as 'metasomatic replacement.'

In all cases of true metasomasis the replacing material is introduced by circulating waters, frequently acting from above downwards, and the solvent action of the water is increased by the presence in it of such compounds as alkaline carbonates, sulphides, silicates, carbonic acid, or the humic acids, all of which have special actions on the country-rock.

Waters charged with mineral matter in solution, acting on a set of strata of varying composition, such as sandstones and limestones, have a selective capacity, for it is noticed that the metalliferous materials are deposited in rocks of special composition. For instance, let us imagine waters acting along the plane of contact of an igneous rock, fairly rich in iron, and a set of alternating grits and limestones, as shown in the figure.

The iron of the igneous rock will pass partially into solution during the process of weathering, and a chemical reaction will take place between this solution and the limestones, resulting in the deposition of an iron ore, and the passage of an equivalent mass of limestone into solution within the region through which the water circulates.

It has been found convenient to restrict the use of the term 'metasomatic' to those chemical replacements
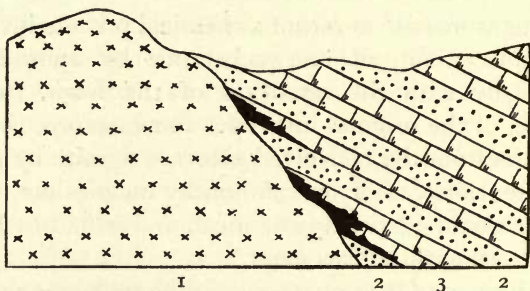
FIG. 45.—SECTION TO ILLUSTRATE THE INFLUENCE OF ROCK-COMPOSITION ON THE POSITION OF METASOMATIC ORE BODIES.

1, Igneous rock; 2, grits; 3, limestone.   Black patches indicate ore.

which only take place in rocks through the agency of circulating water.   We thus exclude all those changes brought about by high temperature, and aqueous and gaseous emanations from cooling igneous magmas, which, on account of the attendant metamorphism, would be treated more appropriately under the headings of 'Pneumatolysis' (p. 72), or 'Metamorphism' (p. 331).

Metasomatic replacements are brought about primarily by the selective influence of certain rocks for some

metallic base dissolved in the circulating waters, and are due either to the metal of the solution having a greater affinity for some acid radicle in the rock with which it forms a less soluble compound, or to the acid radicle of the metalliferous solution having a greater affinity for some base in the rock.

Such replacements are most common in the sedimentary rocks, where they are developed on an extremely large scale; but they may, more rarely, be found associated with igneous rocks.

In sedimentary rocks their replacement by metalliferous material may take place at two periods : either at a period following closely on the deposition of the sediment, and before its elevation into land, or at some subsequent time. A great number of metasomatic replacements have taken place soon after the deposition of the rocks in which they occur, and are very often due to a slight change in the dissolved contents of the water beneath which the rocks were deposited. Others are due to the fact that masses of sediment are often raised into land, and again submerged in a sea differing widely, as far as its dissolved contents are concerned, from the one in which the sediments were laid down ; while some deposits own their origin to the circulation of land-waters in joints and fissures.

Ore deposits which owe their existence to metasomatic replacements of the country-rock by metalliferous material may be roughly divided into two classes: bedded deposits, in which the ore body conforms with the stratification of the strata in which it lies; and fissure deposits, in which the ore occupies the walls of a fissure or joint, and may cross the planes of stratification at any angle.

These two classes of ore deposits include under their respective heads the greater number of ores of metasomatic origin, the former embracing the most important iron and manganese deposits, the latter those of silver, lead, and zinc.

Metasomatic ores present certain features by which they may be recognized, and thus separated from those formed in other ways. There is in almost all cases an absence of symmetrical banding or comb-structure in the vein material. There is a notable absence of breccias cemented by vein-stuff, and a general lack of definition between the country-rock and the ore.

We will now proceed to discuss the origin and describe the mode of occurrence of the various metasomatic ore-bearing masses.

Metasomatic Iron Ores.

The ores of iron which owe their origin to metasomatic replacement consist of the carbonate ($FeCO_3$); the anhydrous oxide, hæmatite (Fe_2O_3); and the hydrated oxides, limonite, etc. Occasionally silicates are met with, but by far the most prevalent are the carbonate (chalybite) and oxide (hæmatite). Many limonitic ores are due to the oxidation and hydration of the carbonate by waters, which carry oxygen or alkalies in solution, percolating into the ore, and causing the carbonate to decompose with the formation of ferric hydrate and the liberation of carbonic acid gas.

The source of the iron which gives rise to metasomatic replacements is generally in some land-area of igneous rocks or pyritous sediments, which, during the processes of weathering, yield ferruginous solutions of various characters, dependent on the character of the

rock, the climate, the absence or presence of vegetation, and many other factors. Some idea of the immense quantity of iron leached out of rocks and carried away in solution may be formed from the average composition of river waters. The amount of ferric oxide contained in a cubic mile of water is as much as thirteen tons, all derived from rocks existing above sea-level.

A great number of iron-bearing minerals, including many of the ferromagnesian silicates, allow their contained iron to pass readily into solution during the ordinary process of weathering; and pyrites is easily oxidized to the soluble ferrous and ferric sulphates.

The more basic igneous rocks, those richer in iron and magnesia, would furnish the more highly ferruginous solutions, and at the same time they are more prone to decomposition than those rocks with a higher percentage of silica.

Iron-bearing solutions may bring about metasomatic changes in two ways—either by percolating into some strata, differing in character from those originally yielding the iron, which are capable of bringing about an exchange of material; or they may find their way into a sheet of standing water, at the bottom of which is some porous deposit which will extract the iron by a metasomatic process.

Calcium carbonate is the compound which we find most often suffers replacement under the influence of such solutions, and the cause is not difficult to detect.

Ferrous and ferric salts, such as the sulphate and chloride, are decomposed in the presence of calcium carbonate, with the formation of the carbonate or the oxides of iron, as the case may be; and this is the reason why so many iron ores occur associated with, or

occupy the positions of, limestones in the sedimentary rocks.

If a solution of ferrous sulphate ($FeSO_4$) acts on calcium carbonate, the chemical reaction results in the formation of ferrous carbonate and calcium sulphate, which reaction is expressed in the equation :

$$FeSO_4 + CaCO_3 = FeCO_3 + CaSO_4.$$
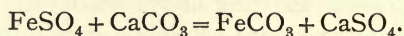
The iron carbonate will replace the calcium carbonate of a rock molecule for molecule, and the calcium sulphate will either crystallize as gypsum, or, if the solution is sufficiently acid, be carried away.

A solution of ferric sulphate [$Fe_2(SO_4)_3$] acting on calcium carbonate will produce hydrated ferric oxide, calcium sulphate, and a liberation of carbonic acid gas :

$$Fe_2(SO_4)_3 + 3CaCO_3 + 3H_2O = 3CaSO_4 + Fe_2(OH)_6 + 3CO_2.$$
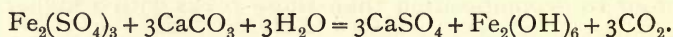
Hæmatite may be produced by the direct action of ferric chloride on calcium carbonate :

$$Fe_2Cl_6 + 3CaCO_3 = Fe_2O_3 + 3CaCl_2 + 3CO_2.$$
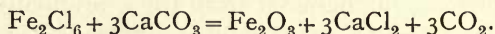
Ferrous carbonate under the influence of oxygenated water, or water containing alkaline carbonates in solution, is decomposed, with the formation of the hydrated sesquioxide of iron, and this is the origin of most limonitic ores of metasomatic character :

$$4FeCO_3 + O_2 + 3H_2O = Fe_2(OH)_6 + Fe_2O_3 + 4CO_2.$$
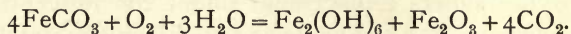
Other limonitic ore deposits result from direct precipitation of the hydrate, and are not replacements ; these will be treated later under the head of ‘ Precipitation ’ (p. 304).

The iron in the solutions which give rise to metaso-

matic replacements will be carried as a different salt according to the rock and the iron-bearing mineral supplying it. From pyritous rocks it will exist either as ferrous or ferric sulphate, according to the partial or complete oxidation of the pyrites. If derived from silicates, it may be in the form of sulphate, chloride, or combined with any acid capable of decomposing the silicates.

With regard to these solutions, it may be safely said that ferrous and ferric sulphates are more prevalent than any other salts of iron.

That chlorides of iron are present in some natural waters is also beyond doubt, especially in such as those which existed in Triassic times, and in which the chlorides of other metals were especially abundant.

Calcareous deposits forming at the bottom of a sea carrying iron salts in solution are most liable to undergo changes of a metasomatic character. Aragonite is more easily acted upon than calcite, and shells of aragonite replaced by carbonate of iron are of common occurrence in most marine ironstones. This change stands out in strong contrast to the extraction of iron in the form of sulphide from sea-water. Muds deposited on the seafloor are often extremely rich in pyrites, which is evidently due to chemical precipitation, a precipitation brought about by the decay of animal organisms in the sediment, and the pyrites is not the result of a chemical replacement of any pre-existing mineral of the deposit.

Often accompanying the change of calcium carbonate to ferrous carbonate or hæmatite is found the analogous replacement of calcium carbonate by dolomite, the double carbonate of calcium and magnesium; and the association of dolomite with deposits of iron ores in

limestone may be taken as an additional proof of their metasomatic origin.

The spathic iron ores of the Coal-Measures are probably precipitations, and not replacements, for it is unlikely that limestones recurred at such frequent intervals in so argillaceous a series of freshwater character. Certain limestone bands which do occur in these rocks are occasionally replaced in part by iron ores, but so far, no argillaceous ironstone has been proved to be a true metasomatic replacement. The alkaline carbonates, such as those of sodium and potassium, meeting with an iron-bearing solution, will precipitate the hydrous carbonate of iron, and this is the more probable origin of the Coal-Measure and many other spathic ores.

The iron ores of metasomatic origin may be divided roughly into two classes:

1. Contemporaneous, in which the replacement has taken place during or immediately after the deposition of the original rock.

2. Subsequent, in which the replacement took place some time after the deposition and consolidation of the original rock.

The former class will include most of the bedded metasomatic iron ores occurring in sedimentary rocks, and the latter, those which exist as irregular patches and veins.

CONTEMPORANEOUS METASOMATIC IRON ORES.

Under the heading of contemporaneous metasomatic deposits may be included most of the bedded iron ore deposits so frequent in the great Mesozoic sedimentary series.

In Great Britain the ores occur interstratified with beds belonging to the Lower, Middle, and Upper Lias, the Inferior Oolites, and the Lower Cretaceous rocks. In other regions they occur largely in the Mesozoic deposits, but several cases of metasomatic ores are known in rocks of much greater antiquity.

In the Silurian system of America, above the Medina Sandstone, we have the great Clinton iron-group existing in the States of New York, Pennsylvania, Wisconsin, Virginia, and several others.

Liassic ores are worked extensively in Hanover. Rocks of Inferior Oolite age yield ores in Lorraine, Luxemburg, Würtemberg, Upper Silesia, and Switzerland.

In England the most important ores occur in the eastern counties, especially in Lincolnshire and Yorkshire.

At Frodingham, in Lincolnshire, a Lower Lias oolitic limestone belonging to the zone of *Ammonites* (*Arnioceras*) *semicostatus* has been replaced by ferrous carbonate. It has a maximum thickness of 25 feet, and a yield of metallic iron which varies from 11 to 35 per cent.

The limestone has been only partially replaced, and the rock is therefore still rich in calcium carbonate ; at the same time much of the ore, especially near the outcrop, has been oxidized to limonite.

The ore is generally a brown oolitic rock in which the greater part of the shell fragments and oolitic grains have been replaced by ferruginous material. It occurs below the horizon of the Cleveland ores noticed below, and thins out with more or less rapidity when traced in a south-easterly direction.

The Cleveland ore occurs in the upper part of the Middle or Marlstone division of the Lias in the zone of

Ammonites (*Amaltheus*) *spinatus*, a horizon characterized by calcareous beds over the greater part of England.
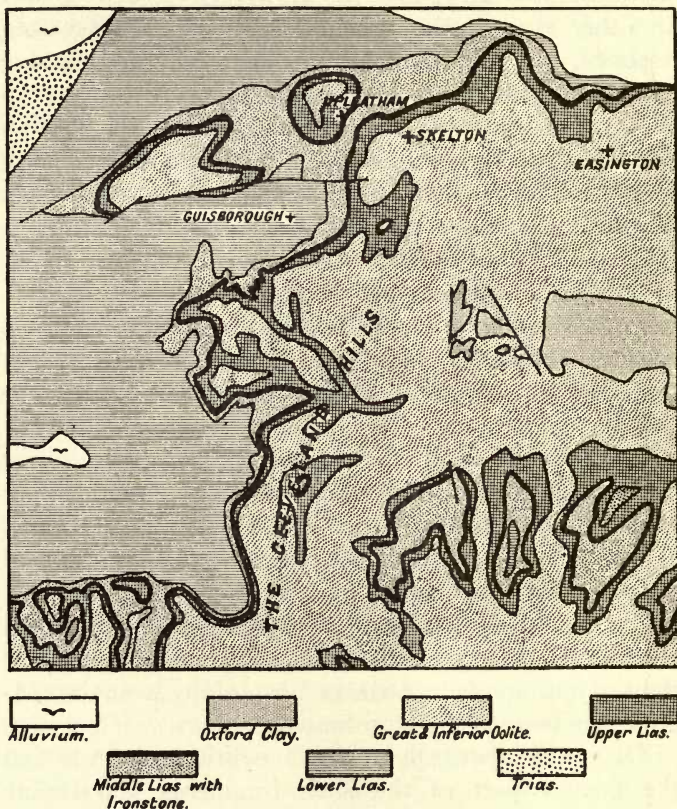
FIG. 46. — GEOLOGICAL MAP OF THE CLEVELAND HILLS, SHOWING THE OUTCROP OF THE CLEVELAND IRONSTONE.

Scale, 4 miles to 1 inch.

As will be seen from the accompanying map (Fig. 46), the outcrop of the ore is most irregular in form, but

these irregularities are due not so much to variations in the dip and strike of the bed, as to undulations in the surface of the country. The outcrop of the Cleveland ore follows those of the other beds in which it occurs, and behaves as any low-dipping bed will in a country dissected by valleys. In the Cleveland district the outcrop of the ore is quite narrow; the low dip of the beds makes the area over which it is possible to work the ore of great magnitude. The ore horizon is covered by deposits of Upper Lias and Inferior Oolites, the whole dipping gently to the south-east with an average inclination of 4° with the horizontal. Numerous shallow folds and undulations affect the strata to a small extent, and there are a few clean-cut faults of no great magnitude.

The Cleveland ore, at Cleveland, occupies a position in the sedimentary series about 480 feet higher than the Frodingham ore, but when traced towards Frodingham the two horizons approximate to within 160 feet of one another owing to the thinning of the strata towards the south-east. The best ore occurs in the neighbourhood of Normanby, Eston, and Upleatham, and it contains from 27 to 35 per cent. of iron.

The iron ores of Laythorp, in Yorkshire, resemble those of Frodingham in more than one respect, and seem to belong to the same horizon in the Lower Lias. The bed has a maximum thickness of about 10 feet, and is evidently a replacement of a calcareous deposit.

Amongst the other true bedded iron ores of metasomatic origin may be mentioned those of Adderbury and Fawler, in Oxfordshire, belonging to the Middle Lias, the Northampton deposits in the Inferior Oolites, which are worked downwards to the zone of *Ammonites*

(*Hildoceras*) *bifrons*, the Neocomian ores of Claxby and Tealby, in Lincolnshire, and the Weald of Kent.

In Continental Europe, similar ores occur in the Lias of Hanover, in the Upper Lias and Inferior Oolite of Lorraine and Luxemburg, in the zones of *Harpoceras opalinum* and *H. murchisonæ*.

The iron ores of Lorraine and Luxemburg, the so-called 'minettes,' have a very variable composition the iron existing as carbonate, silicate, or oxides, including magnetite. Although these ores are doubtless largely due to original deposition, they are in a measure contemporaneous replacements, and additional ferriferous material has been introduced by solutions percolating downward from the pyritiferous *Posidonia* Shales. There are five main seams of ore, covering an area of about 1,100 square miles, averaging about 36 per cent. of iron, and containing only 1·7 per cent. of phosphoric acid.

In Upper Silesia, Switzerland, and especially in the neighbourhood of Aalen (Würtemberg), ores are found which also belong to the *H. murchisonæ* Zone. It will be seen from the above, therefore, that most of the great bedded iron ore deposits in Europe of metasomatic origin belong to well-defined horizons in the Mesozoic sedimentary series.

In America the famous Clinton ores are associated and interbedded with Silurian rocks (Llandovery), and occur above the Medina Sandstone. They cover a very great area, and have been worked in the Western States of New York, Pennsylvania, Wisconsin, Virginia, Kentucky, Tennessee, and Alabama. They are often oolitic, but some of the deposits consist largely of calcareous organisms, such as bryozoa, corals, etc.,

replaced by iron ore, and cemented by secondary calcium carbonate in the form of calcite, in such a manner as to prove that much of the replacement of calcium carbonate by iron ores took place before the cementation of the rock as a whole. This character has also been noticed in the case of the Frodingham ores described above.

IRON ORES DUE TO SUBSEQUENT REPLACEMENT.

We now pass on to consider another and most important group of deposits of iron oxides and carbonates. Like those described above, they owe their origin to the replacement of limestone, and occasionally of siliceous rocks, by ferruginous material, but differ in the fact that they seldom occur as true interstratified deposits, and also were introduced from some outside source long after the containing rock had consolidated and taken on the characters which it now possesses.

These ores, which include the best-known hæmatite deposits, occur in two ways, either replacing the walls of a fault or joint, or at the junction of two kinds of strata of different porosity—in either case along some line that admits of the free passage of mineral-bearing solutions.

Such ore masses are of most wide distribution, and occur all over the world, chiefly associated with limestones.

In Britain, the hæmatite deposits of South Wales, Cumberland, and Lancashire, occur in the Carboniferous Limestones series, and are due either to the influence of the highly ferruginous Triassic and Permian seas, under which the Carboniferous rocks were locally submerged, or to iron compounds leached out of the overlying

Triassic, Permian, or Carboniferous rocks, and re-deposited in the underlying limestones by metasomatic action.

In a few other districts in the British Isles, but more especially on the Continent, deposits of like nature and origin occur associated with limestones of many ages.

In such districts as the Pyrenees, the Alps, and the Carpathians, a long and continued series of earth-movements has resulted in a succession of folds, faults, and unconformities; limestones have been thrown against rocks of widely different character, and have been covered at later periods by seas and sediments, containing much mineral matter. It is not surprising, therefore, to find that in such regions as these the replacement of limestones by iron ores is a most marked phenomenon. In the British Isles the most important ore deposits of this character are associated with the Carboniferous Limestone series, and occur chiefly in the districts of South Wales, Cumberland, and North Lancashire.

In the district of South Wales, including the Forest of Dean, the ore occurs as hæmatite and limonite, forming irregular deposits either within the limestone or at its junction with some other rock. In the case of ores within the limestone, they lie more or less along the planes of bedding and jointing, and are connected by several small ore-bearing channels with the upper surface of the rock. Occasionally the ore has formed at the junction of the limestone with the overlying shales of the Millstone Grit series, or with the Triassic rocks which cover it uncomformably.

It is worth remarking that a great number of im-

portant hæmatite deposits seem dependent on, or are at any rate connected with, unconformable conditions.

The figure below shows the more usual mode of occurrence of hæmatite in the South Welsh deposits. It will be noticed that the distribution of the ore seems to be governed by two factors—firstly, by the position of the ferruginous Triassic conglomerate; and, secondly, by the line of junction between the limestone and the overlying impervious shales of the Millstone Grit series.

Ferrous carbonate is rare in these deposits, for, as has been stated above, the ores are chiefly oxidic in

FIG. 47.—SECTION TO ILLUSTRATE THE MODE OF OCCURRENCE OF HÆMATITE IN THE CARBONIFEROUS LIMESTONE SERIES OF SOUTH WALES.

1, Carboniferous Limestone; 2, shales of the Millstone Grit; 3, Trias (New Red Sandstone); 4, superficial deposits.

character; but it is by no means improbable that the ore was originally deposited as carbonate, and subsequently oxidized. At the same time it must be borne in mind that it seems possible to have hæmatite deposited directly from ferric iron solutions under the chemical influence of limestones, according to the following equation:

$$3CaCO_3 + Fe_2(SO_4)_3 = 3CaSO_4 + Fe_2O_3 + 3CO_2.$$
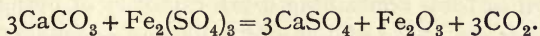
Ferrous iron solutions, as we have seen previously, will deposit ferrous carbonates.

The metasomatic character of the South Welsh ore is clearly demonstrated by thin sections, which by transmitted light show crinoids, polyzoans, and other organic calcareous remains, replaced by the red oxide of iron.

In the North of England occur the still better known hæmatite deposits of Cumberland and North Lancashire; they are of identical character, and both are associated with Carboniferous Limestone. The Cumberland district comprises the Carboniferous area of Cleator Moor, on the border of the Whitehaven coalfield, while the North Lancashire district lies chiefly in the neighbourhood of Furness. The ore deposits of these two districts occur in pockets, chiefly along fault-lines and joints, and evidently belong—as is the case in South Wales—to a period long subsequent to the deposition of the limestone. They yield, on an average, 50 per cent. of metallic iron. Their metasomatic character is proved beyond doubt by the occurrence of hæmatite pseudomorphous after scalenohedra of calcite, and by the presence of brachiopod shells, crinoids, and other originally calcareous organisms, replaced by iron ore. At the same time the bedding of the limestone may often be traced through the ore, and thin beds of shale may be seen passing from the ore to the unaltered rock without interruption.

Associated with the lead and zinc veins of Denbighshire and Flintshire, in North Wales, are a few veins and pockets of hæmatite, which are interesting on account of their containing a fair quantity of manganese as oxide, and some nickel and cobalt as pyrites. These ores occur in the Carboniferous Limestone series at Cwm.

In the case of the North of England ores, it has been suggested that the iron was introduced in the form of choride, but the sulphate of iron seems to us more probable, especially as it is not an uncommon feature of the hæmatite veins to contain sulphates of the alkaline earths among the gangue minerals.

In the Midland district of England the Upper Coal-Measures occasionally contain thin bands of marine limestone (*Spirorbis*-Limestone), which are often found converted into hæmatite by the action of ferruginous waters.
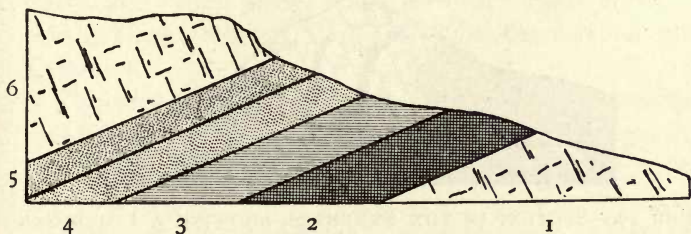
FIG. 48.—SECTION TO SHOW THE MODE OF OCCURRENCE OF THE ANTRIM IRON ORES. (AFTER TATE AND HOLDEN.)

1, Lower basalts; 2, pisolitic iron ore; 3, bole; 4, yellow ochre; 5, lithomarge; 6, upper basalts.

In Ireland, in County Antrim, iron ores in the form of hæmatite, limonite, and the ochres, occur in connection with the basalts, which form such a prominent feature of that district. The basalts themselves contain on an average 5 to 6 per cent. of the metal, and have undoubtedly been the source of the iron in most instances. The ores exist in the form of ferruginous clays, pisolitic deposits, and ochres, lying between the sheets of basalt, and it is evident that they are due to the weathering of the lower layer of basalt before the

upper one was deposited. The action giving rise to them is partly physical, partly chemical, and is analogous to that which played a part in the formation of certain bauxites (p. 264).

The above figure gives an idea of the mode of occurrence of these ores.

Similar deposits are found associated with the basalts of the Faroe Islands and Iceland, which are of the same period of eruption.

There are a great number of districts abroad which
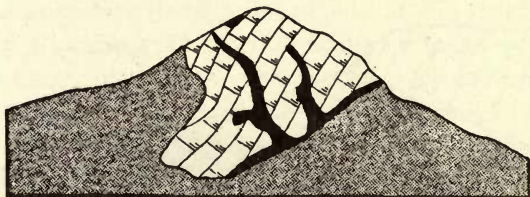
FIG. 49.—SECTION IN THE PYRENEES, SHOWING A LIMESTONE MASS FOLDED AMONG METAMORPHIC SCHISTS, AND PARTIALLY REPLACED BY ORE.

contain iron ores similar to the above, and of identical origin.

In Spain, especially in the Eastern Pyrenees, and in the districts of Torrente, Cartagena, Vizcaya (Biscaya), etc., hæmatite and limonite occur in a limestone series in a manner suggesting metasomatic replacement.

The general mode of occurrence of the ores is indicated in the figure above.

In Greece, as at Laurium and Hilarion, the ore lies at the summit and base of a calcareous series, following the line of demarcation between it and the shales by which it is bounded on either side.

At Pazzano, in Calabria, hæmatite is met with at the base of Triassic limestone, the ore following the plane between the calcareous rock and the argillaceous sediments below.

The Triassic limestones of the Alps and Carpathians have suffered local replacement to a considerable degree, and have given rise to valuable hæmatite and limonite deposits.

The great hæmatite masses of the island of Elba, which are so justly famous, occur chiefly on the eastern and south-eastern coasts in several well-defined districts, the chief areas, taken in order from north to south, being those of Rialtano, Rio, Terra-Nova, and Calamita.

The ores are hæmatite, often beautifully crystalline, and limonite; occasionally small quantities of magnetite are met with, presumably formed by subsequent metamorphic action.

They are all replacements of limestones, which are chiefly of Triassic age. Sometimes all trace of the original bed of limestone has been removed, and so complete has been the interchange of material that we find a fairly compact bed of ore taking its place, and resting directly on Palæozoic rocks. Various periods have been assigned to the formation of these ores, but it is now generally accepted that the replacement of the limestones was brought about by ferruginous solutions which found their way into the calcareous rocks in post-Eocene times.

Ores similar to those of Elba have also been met with in Italy at Orbetello, at Campiglia in Tuscany, and in the Apuan Alps.

In the United States of America iron ore deposits

of metasomatic origin are numerous and well displayed —such, for instance, as in the Tintic district of Utah, where the ore has formed at the junction of an igneous rock (monzonite) with a limestone; and the Salisbury
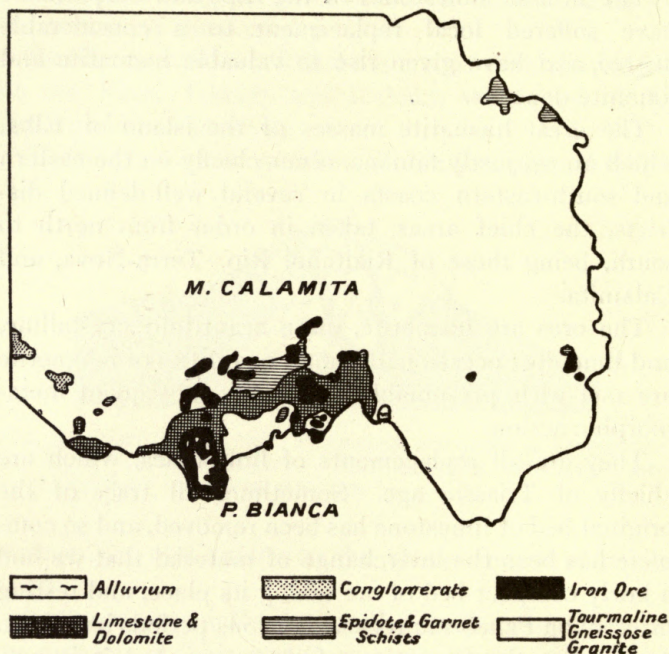
FIG. 50.—MAP OF THE SOUTH-EASTERN PORTION OF THE ISLAND OF ELBA, TO SHOW THE DISTRIBUTION OF IRON ORE (HÆMATITE).

Scale, 1 mile to 1 inch.

district in Connecticut, where large limonitic deposits exist in a limestone series, deposited by waters descending from the overlying pyritiferous Berkshire shales.

In the island of Cuba, to the east of Santiago, iron-

compounds leached out of the basic igneous intrusions of the Sierra Micaro have been deposited as hæmatite in Jurassic limestones at their contact with the igneous rocks. To the west of Santiago similar ores occur, but are less valuable owing to the high percentage of phosphoric acid they contain.

So far we have been dealing solely with the replacement of limestones by iron ores, but ferruginous solutions occasionally replace rocks of a different character.

Many instances are known of hæmatite and other iron ores replacing diabase dykes and other basic or intermediate igneous rocks, but it must be remembered that such rocks are rich in calcium-minerals, which weather with extreme ease under ordinary atmospheric conditions.

Replacements of diabases by iron ores may be cited from the Vosges and Harz Mountains, and are known to have taken place in a modified degree in the Lake Superior region.

The ores of the Lake Superior region possess certain characteristics which cause them, so far as their origin is concerned, to stand more or less alone. Although they seem to be undoubted metasomatic deposits, the conditions under which the replacement took place, as well as the rock replaced, differ from any we have considered before.

The Lake Superior iron-bearing strata form a belt of rocks indicated on the map as occurring in the great pre-Cambrian Huronian formation, and as lying between the Keweenawan rocks and the great Archæan fundamental complex.

They consist of cherty iron carbonates, which are the chief original sediments of this group of rocks; the iron

was directly precipitated from solution as carbonate, after the manner of many spathic iron ores (p. 314), and was presumably derived from the more ancient igneous rocks of the Lake Superior region, many of which were basic in character and proportionately rich in iron compounds.

Archaean.   Huronian.   Keeweenawan.   Post-Algonkian.
(Iron bearing).   (Copper bearing).
Algonkian.
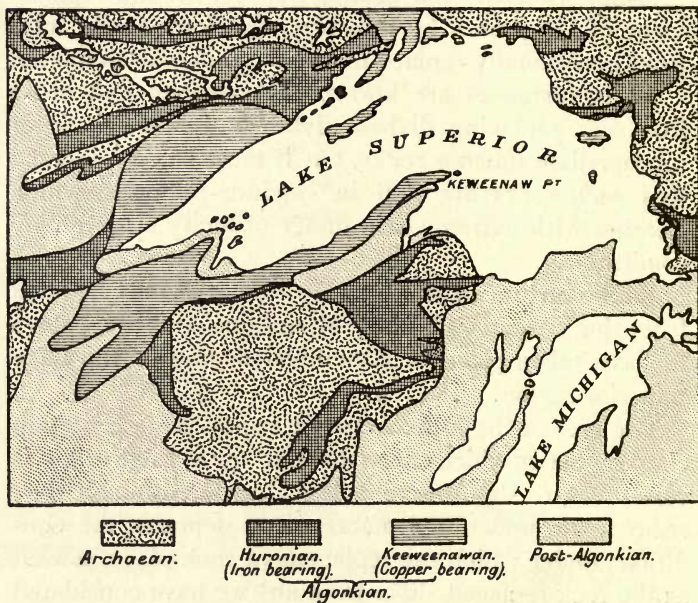
FIG. 51.—MAP OF THE LAKE SUPERIOR REGION.
Scale, approximately 150 miles to 1 inch.

The cherty iron carbonates, by metasomatic changes, pass insensibly into ferruginous quartz schists, jaspers, and magnetite and hæmatite schists, and furnish a most striking example of the manner in which sediments may pass into crystalline schists by a process

independent of contact or regional metamorphic action.

The ores have been worked in several areas around Lake Superior—namely, the Maraquette, Crystal Falls, Menominee, Penokee, Gogebic, Mesabi, and Vermilion districts. In all cases, except in the Mesabi district, they have an identical origin and mode of occurrence. It will be sufficient, therefore, to give the details of one region only.

Perhaps one of the best-known districts is Vermilion in Minnesota. The region is composed largely of cherty iron carbonates, which were deposited as sediments, resting on an Archæan floor, which is composed of a series of basic igneous rocks known as the 'Ely greenstone.'

The cherty carbonates have undergone in the first instance a local transformation into highly ferruginous jaspers and iron-bearing schists. But the great ore deposits exist either at the junction of these rocks with the underlying greenstone, or along lines of fault traversing the sedimentary series. In each case the ores are the same. When they occur at the junction of the igneous rock and the sediments, they tend to congregate in the synclinal troughs in which the rocks have been folded. Those in the sediments either rest on some impervious part of the series above its base, or are governed by some dyke or fault traversing the series. It is usual for the iron-bearing formation to be the hanging wall—that is to say, for it to occur on the upper side of the ore deposit.

Since the junction between the igneous rocks of the Archæan and the iron-bearing formation is a direction of easy flow for percolating water, it is along this line

that the metasomatic changes have been most intense ; the igneous rock has been more or less completely chloritized, and the lower layers of the iron-bearing formation replaced by ores.

In the case of ores occurring within the formation along the lines of faults or dykes, it is noticed that the ore gradually diminishes in richness as the distance from these lines increases.

A study of the various Lake Superior iron-bearing districts has caused the ores of this region to be
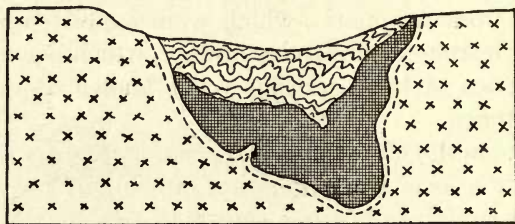
FIG 52.—SECTION SHOWING IRON ORES IN THE SOUDAN FORMATION, VERMILION DISTRICT OF MINNESOTA.

The ore replaces the ferruginous jaspers at their junction with the underlying igneous rock.

regarded as true replacement or metasomatic deposits. Furthermore, it has been proved that the replacement took place after the district had been affected by earth movements, and many of the cherty carbonates and jaspers brecciated. The cherty carbonates contained originally large quantities of ferrous carbonate. This, under the influence of carbonated waters, was dissolved and carried downwards, often along well-defined channels now marked by ore deposits. When two or more streams converged and met at the bottom of a synclinal trough, the metasomatic action was most marked.

The igneous rocks underlying the district, on weathering under the influence of percolating waters, would yield a considerable amount of alkaline carbonates, which would aid in the solution of the silica of the jaspers and cherts, and would help to bring about their replacement by iron ores.

The Mesabi district differs not so much in the mode of origin of the ore, as in the fact that the iron-bearing formation has a somewhat different character. In the cherty rocks of the other districts the iron existed as ferrous carbonate, but in the Mesabi district it was originally deposited as a silicate, to which the name 'greenalite' has been applied.

The average composition of the iron ores of the Vermilion, Mesabi, Marquette, Menominee, and Gogebic ranges is as follows: Iron from 56·29 to 65·00 per cent.; phosphorus, 0·044 to 0·09 per cent.; silica, 3·63 to 11·77 per cent.; alumina, 1·2 to 1·99 per cent.; manganese, 0·04 to 2·44 per cent.; lime, 0·17 to 1·71 per cent.; magnesia, 0·11 to 1·82 per cent.; sulphur, trace to 0·014 per cent.; organic matter and loss, 2·22 to 10·7 per cent.

Similar to the iron ore deposits of the Lake Superior region are those of Bechuanaland, Griqualand West and Rhodesia, in South Africa; and in New Zealand those at Parapara. The ores of Bechuanaland and Griqualand West are associated with a great calcareous series forming a member of the Transvaal System. This limestone is known as the Campbell Rand Limestone and Dolomite, and is succeeded by the Griqua Town Group, a ferruginous series of jaspers, cherty carbonates, and magnetite schists.

The ores occur along lines of brecciated limestone

and dolomite, marking, it is supposed, old subterranean water channels. The replacement has in many instances been most complete, and the removal of much calcareous matter has often resulted in the lowering of the overlying Griqua Town series. The diagram given below shows the general manner in which the ores, which are chiefly limonite and hæmatite, occur.

In the South Island of New Zealand, at Parapara in the Cape Farewell Peninsula, is a group of strata tentatively classed as Silurian, and overlain by coal-bearing Tertiary sediments.
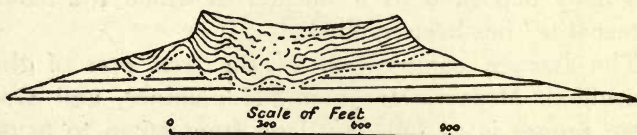
Fig. 53.—Section across Ramages Kop, Berkly West, showing the Relation of the Griqua Town Series to the Campbell Rand Limestone. (After A. W. Rogers.)

The lower series consists of much folded hornblende and felspathic schists, sideritic limestones, and cherts.

The ores are metasomatic replacements of siliceous rocks, and occur in broad synclinal areas where the ferruginous solutions from above were concentrated in a trough of some impervious stratum.

Metasomatic Deposits of Alumina as Bauxite.

Alumina in its anhydrous form (Al_2O_3) is not a common mineral in Nature, although it occurs as corundum in several districts (pp. 57, 344). The impure hydrated oxide, $Al_2O_3.2H_2O$, to which the name 'bauxite' has been given, is met with in greater quantity.

It takes its name from the district of Baux, near Arles, in France, where it is found in association with cal-careous beds.

This mineral rarely exists in a pure state, and, as would be expected, contains varying proportions of ferric iron, replacing part of the alumina, and some silica. The percentage of alumina in the better-class ores ranges from 60 to 75, and that of the silica from 1 to 3. It is used extensively as an ore of aluminium, and as such finds a ready market, but at the same time it is also employed in the manufacture of certain of the alums.

Many of the bauxite deposits seem to be true chemical precipitates (p. 312), but others, from their mode of occurrence, suggest a metasomatic origin.

At the type locality of Baux and several other localities in France, also in the Georgia - Alabama districts of the United States, the bauxite deposits are intimately associated with limestones, in which they occur either as masses of irregular shape or as well-defined beds.

In the Georgia - Alabama district their mode of origin has received some attention. The district is one of Palæozoic limestones underlain by pyritous shales, and dissected by numerous highly inclined fault-planes. Descending meteoric waters acting on the pyrites of the shales give rise to ferrous sulphate and sulphuric acid. The sulphuric acid attacks the aluminium sili-cates of the shale, producing alum and aluminium sulphate, which are carried upwards by the ascending currents.

The ascending solutions of aluminium sulphate, mixed probably with a certain amount of iron sulphate, on coming in contact with the limestone, will act meta-

somatically upon it, forming calcium sulphate, and depositing the hydrated oxides of alumina and iron.

The bauxite deposits as worked in the Georgia-Alabama district consist of layers and masses of ore enclosed in a residual clay, the result of prolonged weathering of the limestone series under somewhat special atmospheric conditions.

Bauxite is also found embedded in clay at Oberhessen and Vogelsberg in Germany.

In the Puy-de-Dôme country of Central France, the Westerwald, Vogelsberg, and the North of Ireland, bauxite occurs in association with basaltic rocks, and is regarded as having been formed from these igneous masses by an obscure metasomatic process.

The deposits of Baux occur as irregular masses in Cretaceous limestones, and it has been suggested that they were laid down by the agency of mineral springs. Such an origin is extremely likely, but at the same time the action which brought about the precipitation was almost certainly metasomatic, and dependent on the chemical action of the limestone.

Lead and Zinc Metasomatic Deposits.

The ores of lead and zinc which owe their origin to metasomatic replacements are most commonly the sulphides, galena (PbS) and zincblende (ZnS), and more rarely the carbonates, sulphates, and silicates, cerussite ($PbCO_3$), anglesite ($PbSO_4$), calamine ($ZnCO_3$), and smithsonite ($Zn_2SiO_4H_2O$). Lead and zinc ores are frequently found in association with limestones; they generally occur together, and may include some silver and copper—the former existing as argentiferous galena,

and the latter as pyrites (chalcopyrite)—also compounds of cadmium. Zincblende and galena seem in almost all cases to be original minerals; but the carbonates and sulphates of lead and zinc are more often formed in the upper part of the ore body or lode from the sulphides by the action of percolating meteoric waters. Smithsonite, for example, may often be noticed to replace the other ores and gangue minerals; it has been found pseudomorphous after fluor, calcite, and even galena.

The metals lead and zinc have been mined in limestones of almost every age all over the world; but in our own country by far the greater number of metasomatic deposits yielding ores of these metals occur in the great Mountain Limestone or Carboniferous Limestone Series, and in all cases their formation can be proved to have taken place long after the deposition of the limestone, usually during some period of earth movement and extensive unconformable conditions.

The ores of lead and zinc often offer the clearest evidence of metasomatic replacement; fossils of a calcareous substance have been replaced by the sulphides or carbonates of these metals, the ore retaining their external form, and sometimes even their internal structure. Such cases may be cited from Cumberland, in our own country; from Monteponi, in Sardinia; and from Iserlohn, in Westphalia.

In England and Wales, in Carniola, Westphalia, Baden, the Veille Montagne district, Monteponi and Malfatano districts of Sardinia, Leadville and Silver Peak in Colorado, Wythe County in Virginia, the Eureka district of Nevada, and a great number of other localities of equal importance, ores of lead and zinc

occur associated with limestones in a manner indicating their metasomatic origin.

The metallic minerals occupy fissures formed either by faults or joints, and extend more or less irregularly, as was the case with the iron ores associated with limestones (p. 249), into the surrounding rock.

The ore-masses have been deposited from solution, and are due primarily to a chemical selective influence which the limestone exerted on the mineral-bearing solution. They thus differ from true vein-deposits in which the country-rock played no essential part in the formation of the lode.

The mineralizing solutions in almost every case of metasomatic lead and zinc deposits came from above downwards, thus differing from many of the solutions which have given rise to true vein deposits.

There are, however, good examples of metasomatic replacements which have had a hydrothermal origin— that is to say, have resulted from the action of heated solutions rising from below.

We have already stated that metasomatic deposits of lead and zinc are generally restricted to some rock, such as limestone, which is capable of interacting with percolating waters, and causing them to deposit their metalliferous contents; this, therefore, supplies us with the reason why so many lead and zinc deposits deteriorate and ultimately fail in depth.

It is obvious that the limestones did not originally contain the metals which are now collected in the veins and fissures traversing them, and the source may generally be found in some series of igneous rocks or sulphide-bearing sediments, either exposed at the surface or subjected to weathering influences below-ground.

We must look, therefore, upon the ores as resulting from metallic solutions percolating the limestone from some sea beneath which it was submerged, or from some series of rocks of different character occurring above it or in juxtaposition. As regards the nature of the solutions which carried the metals, and the reaction, between them and the limestone, which resulted in the deposition of the ore, there is a great deal of uncertainty.

The ores themselves give but little indication of the solutions which gave rise to them, and we must turn, therefore, to the associated 'gangue' minerals for the greatest available information.

With the ores of lead and zinc there invariably occurs a well-defined series of minerals which form a considerable part of the metasomatic deposit. These minerals include dolomite, chalybite, witherite ($BaCO_3$), barytes, fluorspar, and others. From the intimate association of such minerals with the metallic sulphides galena and zincblende, it would be fair to assume that they were given rise to by the same mineralizing solutions.

Sulphides may be precipitated from metallic solutions of sulphates by the reducing agency of organic matter in a limestone, or they may be carried as sulphides in solution, and be deposited as such, should the limestone react with the solvent.

There is reason to believe that all lead and zinc metasomatic deposits consisted originally of the ores galena and zincblende; and that these ores were not formed in many cases by the reduction of sulphates, but were carried as sulphides in solution to the place of deposition.

In mineral springs of the present day, lead and zinc

are known to exist as sulphides held in solution by acids or by alkaline sulphides.

Neither lead nor zinc sulphides are very insoluble, their precipitation, as is well known, being retarded or prevented by free acids.

Assuming that these metals were carried in solution as sulphides, it seems most reasonable, in point of view of the other minerals present in the deposits, to suspect one or more of the alkaline sulphides of being the solvent in most cases, especially as we know that the sulphides of the alkaline earths, such as barium sulphide, will dissolve several minerals including the red silver ores (pyrargyrite and proustite) without change. Let us take the case of barium sulphide. Acting on a limestone, it would cause the formation of barytes and the solution of part of the calcareous matter; at the same time the metallic sulphides would be deprived of part of their solvent, and deposited in the place of the dissolved limestone.

A point in favour of the metallic sulphides being carried as such in solution is the apparent solution and redeposition of galena. In some districts it has been observed that a surface enveloping the richest ore deposits bears, as regards position, a more or less constant relation to the present surface of the ground and the hydrostatic level. If such be more than a mere coincidence, it would point conclusively to the solution of lead sulphide in the upper part of the enclosing rock, and its redeposition at a lower level.

Fluorspar in these deposits clearly occurs as a metasomatic replacement resulting from the action of some dissolved fluoride on a limestone:

$$CaCO_3 + RF_2 - CaF_2 + RCO_3.$$
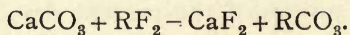
The more soluble carbonate would be carried away, and its place taken by the less soluble fluoride of calcium, which often occurs pseudomorphous after calcite and dolomite.

Fluorspar is not by any means a constant associate of either galena or zincblende, but its occasional occurrence with these ores suggests that the mineralizing solutions were not likely in such cases to have contained alkaline carbonates, for these act on calcium fluoride with the formation of calcium carbonate, thus—

$$R_2CO_3 + CaF_2 = CaCO_3 + 2RF.$$
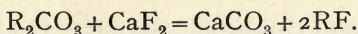
For a similar reason we suggest that the fluoride was not carried in combination with the alkali metals alone, for under those circumstances a metasomatic replacement of limestone by fluorspar would not be possible.

Fluorspar may, however, be formed by the action of the alkaline fluorides on calcium silicates, the more soluble alkaline silicates passing away in solution.

In the case of the fluorspar deposits associated with calcareous beds, it is extremely difficult to imagine in what form the fluorine was introduced; but it must be remembered that there are several sparingly soluble metallic fluorides, such as those of silver and lead, and it is also possible that the double fluorides of the metals played a part.

It is also possible that the mineralizing solutions were acid in character, and would thus not contain free alkaline carbonates, such as is the case with most alkaline percolating waters.

As has been stated previously, the carbonates, sulphates, phosphates, and silicates of lead and zinc are

usually due to alterations by percolating waters in the upper parts of lodes which carry sulphidic ores; at the same time they often exist as metasomatic replacements. In the presence of limestone the solutions of sulphates, produced by the simple oxidation of the sulphides, will be acted upon by the calcium carbonate, causing the precipitation of the metals as carbonate or sulphate, according to the alkalinity or acidity of the solution. The calcium sulphate formed in such cases would either be retained in the vein or carried forward in solution.

Both lead and zinc sulphates under the further action of percolating waters charged with carbonic acid may be converted into carbonates, this being a frequent change in the upper part of lead and zinc lodes.

Zinc silicate can be formed from the sulphide by the action of alkaline siliceous waters; the alkaline carbonates are the most usual solvents for silica in natural waters.

The phosphates of lead and zinc are generally of secondary origin, but there are instances where deposits of such minerals are metasomatic in character, and have had their origin in highly phosphatic beds traversed by mineralizing solutions. A striking example is the case of a bone-breccia filling a cave in the limestones of the Broken Hill district of Rhodesia, where the calcium in combination with the phosphoric acid has been replaced largely by zinc, giving rise to the zinc phosphates hopeite, tarbuttite, etc.

Although the metasomatic ores of lead and zinc have had presumably an identical origin, and are often associated, it will be well to divide the following examples into two, separating as far as possible those

in which lead ores preponderate from those which are more strictly characterized by zinc.

Metasomatic Lead Ores.—In Great Britain lead has been mined in several districts from very early times. These districts include Flintshire, Derbyshire, Durham, Cumberland, and to a less extent Lancashire. In all cases the deposits are governed by fissures in rocks of the Carboniferous Limestone Series, or by the junction of a limestone with some impervious rock which most often forms the hanging wall of the lode.

In Flintshire the chief ore is galena, yielding from 14 to 18 ounces of silver to the ton. It is associated in the main veins with some zincblende; but this mineral is practically absent from the cross-courses, and its place is often taken by copper pyrites. The majority of the veins occur along fault-fissures having a general east and west direction; these fissures are probably of pre-Triassic age, and have been the channels for water which had acted on a variety of rocks.

The deposition of the lead ores has evidently been controlled by the overlying pyritiferous Holywell Shales, which probably furnished a good deal of sulphur in the form of sulphates and sulphuretted hydrogen, and also by beds of shale existing in the Limestone Series itself.

In Denbighshire the ores are similar to those of Flintshire, but at the same time the lodes carry more zincblende and copper pyrites. Nickel and cobalt also occur as sulphides, and iron and manganese as oxides.

The upper part of the lodes has undergone oxidation, with the formation of gossan to a considerable depth, and the transformation of the sulphides to carbonates.

In the great Talargoch mine, now disused, it was observed that the flats were richer in lead than the

veins, but contained less silver.   This probably points, as does the presence of copper, cobalt, and nickel, to the introduction of the metals at more than one period.

Secondary changes have resulted in solution and re-deposition of the ores in cavities, but most of them are of true metasomatic origin.

The Derbyshire lead ores were among the first to be worked in Britain, and they are noted for their asso-ciated gangue minerals, fluorspar and barytes, two minerals highly characteristic of lead veins in lime-stones, and which have been profitably worked.
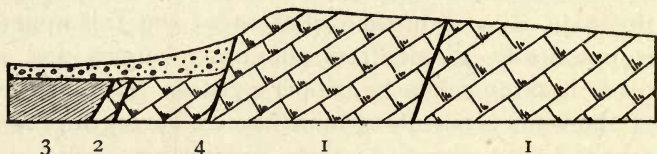
FIG. 54.—DIAGRAMMATIC SECTION ACROSS TALARGOCH
VEINS.   (AFTER STRAHAN.)

1, Grey and white limestone; 2, black limestone; 3, shales; 4, Talargoch vein. The vein to the right carries hematite and copper ores.

The ores consist of galena with some zincblende, and in the upper part of the lodes which usually occur along fault-fissures or joints, cerussite and calamine.   Some copper pyrites also occurs.

The lead ores of Derbyshire seem to be confined more or less to one horizon in the Limestone Series, and to be governed, as regards depth, by certain sheets of intrusive and extrusive olivine dolerite, locally known as 'toadstones,' through which and below which the ores seldom pass.

Some of the chief districts where galena has been extensively mined are those of Castleton, Bradwell,

Tideswell Moor, Longstone Edge, and Taddington, and most of the deposits are metasomatic in character. Some of the lodes, however, are brecciated, and others show well-defined comb structure; it is probable in these cases that the ores are independent of metasomatic action, and are merely the infillings of cavities and open fissures in the limestones.

In Europe and the other continents, examples of metasomatic lead ore deposits are far too numerous to mention in detail, but the following are a few selected on account of their importance and scientific interest.

Some of the most important deposits in Europe are those of Sala in Sweden, of Raibl and Bleiberg in Carinthia, and of Tunis in North Africa. In America there are the famous deposits of Leadville and Colorado, and similar occurrences in Wisconsin and Utah, as well as the argentiferous galenas of the Eureka district of Nevada.

The Sala deposits occur to the north of Stockholm in Sweden, and are intimately associated with an ancient dolomitized limestone. The ore is chiefly galena, which carries a good percentage of silver.

These deposits have had many origins assigned to them, but none seems so satisfactory as that of metasomatic replacement.

The famous districts of Raibl and Bleiberg in Carinthia are situated in an area composed largely of Upper Triassic limestones and dolomites. The Raibl region is also noted for its zinc deposits, and presents the clearest evidence of metasomatic replacement of the limestones by compounds of the metals. The ore-bearing veins are steeply inclined to the horizontal, and

18

traverse a great thickness of strata; a peculiar feature is that they contain large quantities of the mineral wulfenite, lead molybdate ($PbMoO_4$), formed from the original lead compounds by the action of later percolating waters carrying molybdic acid or soluble molybdates.

Pyromorphite, the chlorophosphate of lead found in the upper portions of many lead lodes, has had a similar origin, being formed by the action of phosphoric acid solutions on pre-existing lead compounds.

In North Africa, associated with the Nummulitic Limestone in the neighbourhood of Tunis, occur several important deposits of galena and cerussite mixed with a certain amount of zincblende and its alteration products. The galena, which is seldom argentiferous, occurs in flat lodes at the unconformable junction of the limestones with a series of mica schists and quartzites. The secondary calamine occasionally shows the most remarkable concretionary structures. It has been suggested that the ores were introduced at some late period in the Tertiary era.

In America the clearest proofs of metasomatic action are displayed by the great lead ore deposits of Leadville, in Colorado, and by those of Utah, Wisconsin, Illinois, and several other States; also important silver-bearing ores occur in the Eureka district of Nevada and in the Sierra Mojada district of Mexico.

The Leadville region is situated on the western side of the Mosquito Mountains, and is composed chiefly of limestone with porphyries and other igneous rocks.

The ores, which are mostly carbonates, exist in a blue-grey dolomitic limestone of Carboniferous age; they include also the sulphides of iron and lead, together

with the chlorophosphate of the latter metal. Silver is occasionally present, combined with the halogens.

The deposits occur chiefly as flats at the junction of the pervious limestone with the less pervious micro-granite, or 'white porphyry'—that is to say, along the line which presented the least opposition to circulating waters.

The source of the metals seems to have lain in the surrounding igneous masses, which also supplied most of the gangue material, such as the compounds of iron and manganese, and barytes. In the case of the barytes it is highly probable that barium solutions resulted from the decomposition of barium-bearing felspars, for this metal not infrequently partially replaces calcium in the plagioclase felspars. A study of the ores of the Leadville district shows that they were deposited from solutions coming from some source above the place of deposition, and were not brought up from below by thermal agencies. It is also more or less obvious that all the metals were originally deposited as sulphides as the result of metasomatic interchanges.

In the neighbourhood of the surface these sulphides of lead and iron (pyrites) would be acted upon by per-colating meteoric waters, giving rise to carbonates, sulphates, chlorophosphates, etc., according to their nature. The iron would probably pass to hæmatite or limonite.

The principal mines of this district are Iron Hill, Carbonate Hill, and Feyer Hill, and the section given below shows a common mode of occurrence of the ore bodies.

The Eureka district of Nevada is also a most impor-tant and instructive lead-bearing region.

The main ore bodies are due to the replacement of a limestone along its faulted plane of contact with impervious quartzites.

The ores in depth consist of the sulphide galena, associated with some iron pyrites, but as the deposits are followed to the surface they take the form of carbonate, oxide, molybdate, chlorophosphate, and arsenate.

An important feature of the Eureka lead deposits is that they contain gold in addition to a fair quantity of silver.
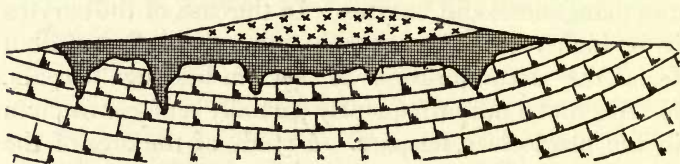
FIG. 55.—GENERALIZED SECTION TO ILLUSTRATE THE MODE OF OCCURRENCE OF THE LEAD ORES IN THE LEADVILLE DISTRICT.

The ore lies between the limestone below and the 'White Porphyry' above.

The lodes are often brecciated by subsequent movement between the hard and soft rocks, and it can be clearly seen that mineralization has taken place both before and after the formation of the breccias.

The accompanying figure depicts in section the usual position of the ore-mass with reference to the limestone and quartzite.

The deposits of both Utah and Wisconsin appear to be associated with a series of dolomitic limestones, and as far as deposition is concerned to be independent of any other rock-masses. They bear no relation to the igneous rocks of the district, but are occasionally overlain by recent superficial accumulations.

The ore is argentiferous galena, and its late introduction is suggested by the fact that certain caves in the limestone have yielded bones impregnated with this mineral.

The deposit becomes rapidly poorer in depth, a character which is presented by a great number of the metasomatic ores of lead and zinc.

The ores of Illinois, which occur in the Trenton Limestone of Ordovician age, end off before the underlying
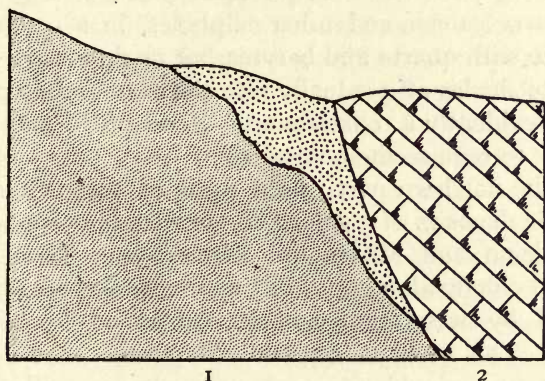
FIG. 56.—SECTION TO ILLUSTRATE THE POSITION OCCUPIED BY THE ORE BODIES IN THE EUREKA DISTRICT.

1, Mount Prospect quartzite; 2, limestone. The ore occurs between the limestone and the Mount Prospect quartzite.

Potsdam Sandstone is reached, just as the majority of the Derbyshire ores do with respect to the toadstones.

In the Cambrian of Dakota, the ore when unoxidized consists of pyrite, argentiferous galena, and small quantities of zincblende. The pyrite occasionally carries gold, and is of earlier formation than the galena. The ore is evidently a replacement of a dolomite bounded by

shales, and is accompanied by much silicification of the surrounding rock, which recalls the 'refractory ores.'

In the Carboniferous Limestones of the same region deposits of lead carbonate pass down into galena, and occur as large irregular masses in contact with a porphyry or partly filling crevices. The irregular masses are the richer in silver, and the infillings are accompanied by the greater amount of secondary silica.

In the Cœur d'Alene Mountains of Montana, fissures traversing quartzites and quartzose shales of Algonkian age, carry galena, and other sulphides, in a gangue of siderite with quartz and barytes, but no fluorspar. The siderite shades off gradually into the surrounding rocks, and is evidently a replacement. Some of the sulphides appear to replace the quartzite.

In the northern part of the State of Arkansas metasomatic deposits of galena and zincblende occur in the Ordovician and Mississippi Limestones. They have formed chiefly along lines of fracture, which are accompanied by brecciation, and are controlled by beds of shale. The ores as originally deposited consisted of galena and zincblende, and as such are still found in depth; but subsequent alteration by descending alkaline and siliceous water has resulted in the solution of the sulphides and their redeposition, together with much secondary silica, at a lower level. The silica has replaced the limestone to a great extent, giving rise to cherts. As already pointed out, the solution and redeposition of sulphidic ores in mineral lodes is not an unusual phenomenon (p. 268).

In Mexico, lead ore exceptionally rich in silver also occurs in limestone, and lies along, or near, the plane of contact of the limestone with a limestone-breccia-

conglomerate. The ores are well displayed in the Sierra Mojada, and yield certain amounts of copper and iron pyrites as accessories.

Metasomatic Zinc Ores.—In Derbyshire and Cumberland, zinc ores, chiefly blende with some calamine, occur, associated with the lead ores of the Carboniferous Limestone Series. It often happens that zinc is more prevalent in the lower part of the veins, and this seems to indicate that the lead compounds, being less soluble, were deposited in the upper portions of the lode, while the zinc was still held in solution until a lower level was reached, and the solution robbed of certain of its constituents. At the same time, zinc sulphide being one of the more soluble metallic sulphides, we can conceive that it might be easily extracted from a mixed lead and zinc lode, and deposited at a lower level by descending waters.

Amongst the Derbyshire ores calamine is fairly abundant, and although it results, as does cerussite, from the alteration of sulphides, it occurs as a true metasomatic deposit due to the zinc solutions acting on the limestone and replacing the calcium carbonate by the corresponding zinc salt.

Still more important are similar deposits in Cumberland, where the mode of occurrence of the ores is identical with those of Derbyshire. The lodes often carry some copper and iron as pyrites, and other metasomatic minerals, such as chalybite.

In the Mendip Hills calamine has been found associated with the Triassic dolomitic conglomerate, a deposit which marks the base of the Triassic sediments in that region. The ore occurs chiefly in veins and pockets, and has evidently resulted from the alteration of zinc-

blende in places; although zincblende is a comparatively rare mineral in the Mendip district, it probably occurs in greater quantity in depth.

The zinc ores, blende and calamine, also occur as metasomatic replacements associated with the galena and hæmatite deposits of Flintshire (p. 271).

Compared with the zinc deposits of the Continent, such as those of Sardinia and the Alps, the English and Welsh occurrences sink into insignificance. The origin and mode of occurrence of the Continental deposits seem to be identical with those we have already considered ; we see the same intimate connection between the zinc and lead ores, for they generally occur together in the same deposit. Such a relation between similar ores of two metals, taken in conjunction with the fact that they are associated with the same gangue minerals, can only point to an identical mode of introduction and deposition.

Amongst the most important metasomatic zinc ore deposits of Continental areas are those of Sardinia, Greece, Belgium, Westphalia, Silesia, the Eastern Alps, and Northern Spain, in Europe; Algeria and the Otavi Mountains, in German West Africa ; and many districts in the United States and Mexico, in North America.

In Sardinia zinc and lead ores are mixed in several districts, but only a part of the deposits can be claimed to have had a metasomatic origin.

The metasomatic ores are associated with limestones and other beds of Ordovician age in the southwest portion of the island. They are met with either at the junction of the limestones with a series of non-calcareous beds, or within the limestones themselves.

The junction of the limestone with the other type of sediment may be either a fault line or a normal plane of sedimentation, the metalliferous deposit following the one or the other as the case may be.

The ores are mixed in character consisting of galena, calamine, and smithsonite (zinc silicate), associated with a good deal of iron in the form of oxide and hydrate. The gangue contains barytes and fluorspar, while the limestone surrounding or bounding the ore body has undergone extensive dolomitization.

The chief districts where zinc ores are raised are those of Monteponi and Malfatano, which have yielded vast quantities of calamine.

In the veins, etc., of Sardinia, which are associated with limestones, it is evident that zinc-charged waters have attacked and replaced the calcium carbonate particle for particle. It is probable, however, that here calamine is a secondary metasomatic deposit, resulting, as in many other cases, from the alteration of zinc-blende; for many of the Sardinia deposits, when followed downwards, are proved to contain a considerable quantity of this sulphide.

The Grecian ores of Attica, south-east of Athens, in the neighbourhood of Laurium, are famous for their extreme thickness, and for the very early date at which they were first exploited. The metal-bearing strata consist of three distinct beds of limestone of doubtful age, separated from each other by non-calcareous rocks.

The ores, as in many cases previously described, occur chiefly at each contact of a limestone band with the adjoining rock, these junctions representing the planes of concentration of the percolating waters.

The ores consist chiefly of zincblende and galena in

a gangue of chalybite, but oxidation has given rise to cerussite, calamine, hæmatite, and gypsum, all of which are found in the upper parts of the deposits. The thickness of the ore body diminishes in each bed of limestone when followed upwards; for instance, in the figure below, the zinc deposits in the lower bed, labelled 1, will be pure, but those in 3 will have a considerable admixture of calcium carbonate.

From the above and some other reasons, it is argued that the zinc-bearing solutions were hydrothermal, came from below, and that they passed through small
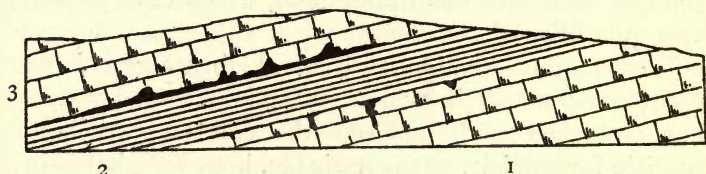
Fig. 57.—Diagrammatic Section to illustrate the Mode of Occurrence of Ore Masses in the Neighbourhood of Laurium.

1 and 3, Limestone ; 2, shales.

fissures in the non-calcareous rocks without depositing their metalliferous contents. In the limestone, however, the presence of the calcareous material caused them to deposit the ores along the junctions of the limestones with the intervening and resistant shaly layer. The solutions would pass on only after the work of replacement was complete.

The Belgian deposits, like those of England and Wales, are confined almost entirely to the Carboniferous Limestone Series, and occur chiefly in the district of Vieille Montagne.

The limestones show extensive dolomitization, a

phenomenon, as we have seen, generally associated with metasomatic metalliferous deposits in calcareous rocks.

The ore is chiefly calamine with some silicate of zinc, and in mode of occurrence recalls that of Laurium mentioned above, as it is generally found at the junction of the limestone with overlying shales.

Although the ores are chiefly carbonates, the sulphides are not entirely wanting, blende, galena, and pyrites, being poorly represented.

In the Vieille Montagne region the metalliferous deposits are clearly dependent on a set of fissures running north-west and south-east, down which the mineralizing solutions have passed.

The Westphalian deposits occur either in the Middle Devonian or *Stringocephalus* Limestone, or more often at its junction with the underlying Lenne Slates. The richest ores have been met with in the districts of Iserlohn and Brilon, and include zincblende, calamine, galena, and iron pyrites. The zinc deposits give the clearest possible proofs that they have been formed in the limestone by a process of substitution.

In the German Empire, the zinc mining district of Upper Silesia is by far the most important. The ores occur associated with the Muschelkalk, the middle, calcareous, division of the Triassic System, lying between the Mottled Sandstones of the Bunter and Keuper.

The greater part of the ores occur in the lower part of the Muschelkalk, in limestones and dolomites which have been designated 'Schaumkalk' and 'Solenkalk'; the ores are the usual assemblage: blende, calamine, galena, iron pyrites, cerussite, and hæmatite.

These minerals have been deposited chiefly in flat lodes, the position of which is confined more or less to

the junction of the Schaumkalk, or metalliferous dolomite, with the underlying Solenkalk, into which the ores pass.

The minerals as originally deposited were sulphides of the metals lead, zinc, and iron, for all the deposits appear to become highly sulphidic in depth; so therefore, as in so many other instances, the presence of calamine, cerussite, and hæmatite, is due to oxidation of pre-existing sulphides.

It has been suggested that the original source of the zinc and lead ores lay in the Schaumkalk dolomite, where they were precipitated at the time of the deposition of the limestone, and that the present great ore deposits owe their origin to a metasomatic secondary enrichment.

In the Alpine region, the richest zinc-bearing region is that of Carinthia, in which the Raibl district is the best known. The ore, which, like those mentioned above, occurs in the Triassic limestones, is chiefly calamine; but a little silicate of zinc is also met with, as well as the minerals cerussite and limonite.

It is interesting to note that the hydrous carbonate of zinc occurs in some quantity, and is a mineral which, as far as laboratory experiments teach us, would be readily deposited by the influence of calcium carbonate on zinc solutions. Why the anhydrous carbonate is in Nature generally much more common than the hydrous salt still requires explanation.

The zinc ores of Raibl are intimately connected with the faulting and jointing of the beds in which they occur. They are usually surrounded by, or associated with, secondary dolomites, but most of the common gangue minerals, such as barytes, fluor, etc., are practically absent. These deposits present the most striking

proofs of the replacement of a limestone, and even its organic remains, by metalliferous material; for it is not a rare thing to find fragments of limestone completely replaced by ore, with the retention of their original structures.

The chief Spanish deposits occur in the province of Asturias. At Santander they are associated with the *Hippurite* Limestone of Cretaceous age, but in the Picos de Europa district the Carboniferous Limestone forms the country-rock. Original blende and secondary calamine with some silicate are the usual ores in both districts; but in the Santander deposits the hydrous carbonate of zinc occurs in addition.

In Africa, in the Little Atlas Range of Algeria, the Tertiary Nummulitic Limestone contains considerable metasomatic deposits of zincblende, which is locally converted into calamine.

The ores occur chiefly at the junction of the calcareous with non-calcareous beds, as is the case in most of the other districts already cited.

Lodes carrying zincblende associated with galena, and having smithsonite, calamine, and copper carbonate, in the gossans, occur in the Malmani dolomites of the Transvaal. They are interesting also on account of their containing the mineral cinnabar.

In the United States and Mexico, zinc ores occur in most of the lead-districts we have already mentioned, as, for instance, in the States of Colorado, Utah, Wisconsin, Illinois, Pennsylvania, etc.

Metasomatic Cadmium Deposits.

The metals cadmium and zinc are extremely similar in nature; they are dissolved by the same solvents, and

are thrown out of solutions in almost all cases by the same precipitant. It is, therefore, not surprising to find cadmium in almost all zinc ore deposits existing under conditions exactly similar to the zinc compounds, and having an identical origin. Analyses of most samples of zincblende show the presence of this metal in small quantities; it probably replaces zinc, in combination with sulphur; occasionally, however, the somewhat rare but pure sulphide, greenockite, is met with, as in several districts in the United States.

Cadmium also occurs in the deposits of zinc carbonate and silicate in almost all of the districts mentioned above where such zinc ores are mined. It is especially abundant in the calamine deposits of Upper Silesia and of the Vieille Montagne district. The calamines of Upper Silesia have yielded as much as 5 per cent. of cadmium.

METASOMATIC COPPER DEPOSITS.

The Sulphides, Carbonates, etc. — Reference has already been made to the occurrence of copper ores in the lead and zinc deposits of metasomatic origin; and although they are generally met with in small quantity only, they occasionally occur in sufficient force to give a distinctive character to the deposit. The ores consist chiefly of chalcopyrite or copper pyrites, and the results of its reduction or oxidation in the form of native copper and oxides of copper; while phosphates, carbonates, and silicates, are not infrequent secondary products.

The mode of deposition of the sulphides in a certain number of deposits, like those formed in limestone or at

its contact with another rock, is similar to that of the sulphides of lead, zinc, and iron; while the other compounds, such as the carbonates, etc., generally result from the action of atmospheric waters on copper pyrites.

The waters which carried the copper and iron in solution may have come from below or above; there is little doubt that these metals were often transported in the form of sulphates, either due to the oxidation of pyrites in neighbouring rocks, or in the form of aqueous emanations from an igneous magma during the later stages of its cooling.

Such solutions in the presence of limestones give rise to the carbonates azurite or malachite, oxides of copper, and gypsum; but the deposition of chalcopyrite is probably governed by the action of the limestone on a solution of the sulphide in an alkaline sulphide, as was the case with galena and zincblende. It has been shown by Doelter that iron pyrites, galena, zincblende, chalcopyrite, and several other natural sulphides, are soluble in sodium sulphide without change.

We may suggest, therefore, that the metasomatic chalcopyrite deposits are due to ascending or descending solutions of sulphides, carrying sulphuretted hydrogen and alkaline sulphides. The carbonates of copper, on the other hand, result from the action of limestone on solutions of sulphates.

The hydrous carbonate, malachite, is most frequently associated with carbonate of iron, and the carbonates of lead and zinc are often present in the same deposit.

Generally speaking, however, metasomatic copper deposits of this character are of rare occurrence, the majority of the copper ores of the world existing as

precipitations lining and filling fissures, their deposition being in no way controlled by the nature or composition of the country-rock.   A few cases, however, of deposits of copper ores which we are led to regard as metasomatic will be cited below.

In the district of Nizhne-Tagilsk, in the Ural Mountains, copper ores have been described as occurring at the junction of limestone with syenite, in a manner suggesting metasomatic replacement of the limestone. The Blagosslowsk deposits, also in the Urals, and those of Banat in Hungary, were probably also of this nature, but have been subsequently metamorphosed.

The ore is largely chalcopyrite, but its alteration has resulted in the formation of the carbonates, azurite and malachite, the phosphates and silicate of copper.

In the United States the copper deposits of Bisbee, in Arizona, appear to be metasomatic replacements.

The ores occur as masses in pockets in the Palæozoic limestones at their junction with shales and igneous rocks, more especially with the great porphyry mass of the Sacramento district, which has produced little or no metamorphism on the surrounding sediments.   There seems little doubt that the metal was introduced as sulphide by solutions which worked along the plane of contact of the igneous rock with the sediments, and which brought about the replacement of the limestone.

The ores have undergone great changes through subsequent alteration by oxygenated waters, charged with sulphates, which percolate from the surface; thus the minerals contained in the upper 200 to 600 feet of the lodes are quite different from those found at a greater depth.

The earliest process of ore formation was the depo-

sition of iron and copper pyrites, zincblende, and some molybdenite.

The secondary changes include the formation of cuprite, malachite, azurite, chalcosite, and many other minerals, together with the elimination of much of the zinc and sulphur.

The original minerals below the weathered zone are chiefly iron and copper pyrites, but some cerussite exists in the limestone.

These ores are for the most part associated with metamorphosed calcareous beds containing such metamorphic calc-silicates as garnet, idocrase, diopside, and tremolite. But the proof of their metasomatic origin lies in the fact that the ore bodies are not confined to the zone of metamorphism, and seem to be more or less independent of it, occasionally stretching far beyond the range of the metamorphic calc-silicates.

In the district of the Hartville Uplift, Wyoming, copper ores such as chalcosite, malachite, etc., replace the ferruginous compounds, and even the matrix, of the lower part of the Guernsey Sandstone Formation, which rests directly on an impervious floor of pre-Cambrian rocks.

In many of the lead and zinc deposits described above, copper ores prove an important accessory constituent of the lodes. In the Sierra Mojada district of Mexico we are confronted with a series of interesting complex lodes of metasomatic origin containing ores of copper, silver, lead, zinc, and iron.

The high-grade copper ores of Monte Catini and Monte Calvi, in Northern Italy, are by some considered to have had a metasomatic origin, and it is quite probable that some of the chalcopyrite masses, such as those

of Nassau, found in altered diabases and andesites (schalstein), and associated with galena and zincblende, may be of a similar nature.

Native Copper.—Deposits of native copper present many features of exceptional interest, for although much of the free metal has been formed in the lodes through the reduction of sulphides, carbonates, oxides, etc., by the action of organic compounds in solution, a certain number of deposits, such as those of the Lake Superior region, are claimed to be true metasomatic replacements.

Reference to the map on p. 258 shows that in the Lake Superior region there occurs a great series of rocks of pre-Cambrian age, the uppermost division of which has been styled Keeweenawan, after the narrow peninsula on the southern side of the lake, where it is exceptionally well displayed. The Keeweenawan Series is succeeded unconformably by the Lower Cambrian sandstones, and contains the chief copper deposits of the region. It consists of a great mass of amygdaloidal lavas and sills, with some beds of sandstone. These igneous rocks and sediments are restricted to the Lake Superior basin, and present remarkably constant features over all the district. The igneous rocks are intermediate in character—that is to say, neither rich in silica nor in the ferromagnesian constituents; they belong to the augite-plagioclase family, and hornblende is seldom met with except as an alteration product.

The native copper occurs as nodules, and even as a matrix of certain breccias, and filling the amygdaloidal cavities in the igneous rocks of the series.

In the Keeweenawan Formation it has been most extensively met with in the State of Michigan, especially in the Keeweenaw Peninsula; it also occurs in the

state of Wisconsin, and at a few localities on the Minnesota coast. With regard to the source of the copper, there seems little probability of its having been derived from the upper sandstones of the Keeweenawan Series, although it has been held that it was originally deposited there in the sulphidic condition, and subsequently leached out as sulphate, carbonate, and silicate, to be redeposited as native copper. Its derivation from the lavas themselves seems just as improbable, but, whatever its source, it is clear that the native copper was deposited by the agency of solutions, containing the sulphate, carbonate, or silicate of the metal, acting metasomatically on the igneous rocks.

The reduction was brought about by the peroxidation of the ferrous oxide molecule in the ferromagnesian silicates of the lavas, aided by the action of the ferrous oxide of the magnetite, and of the unindividualized magma forming the glassy layers of the eruptive rocks.

In the neighbourhood of the copper deposit the country-rock shows marked signs of alteration due to the influence of percolating meteoric waters, and secondary minerals, such as epidote, prehnite, and chlorite, become abundant.

The metal often occurs filling the amygdaloidal cavities, and there is little doubt that in this case also it has been reduced from cuprous or cupric salts by the action of ferrous salts given rise to by the destruction of ferromagnesian silicates.

Metasomatic Antimony Deposits.

Certain deposits of antimony ores, especially of the oxide of this metal, are now regarded by many as

metasomatic in origin. We may mention those of Algeria and of the Sonora district of Mexico.

The Algerian deposits occur in the province of Constantine, in the neighbourhood of Jebel Hammamet. The ore, which exists chiefly as oxide, is found in irregular layers running parallel to the beds of black limestone of Lower Carboniferous age with which it is associated. These ores were at one time thought to be of simple sedimentary character, deposited contemporaneously with the enclosing rock. It seems, however, that the idea of a metasomatic replacement of the limestone more closely approximates to a true explanation of the facts observed.

The Mexican deposits are similar to the above in mode of occurrence, and are associated with a limestone series of approximately the same age. The ore consists chiefly of the hydrated oxide, $H_2Sb_2O_5$.

Like the natural sulphides of iron, copper, etc., the sulphide of antimony is soluble in solutions of the alkaline sulphides, but the above deposits were probably formed by the action of calcium carbonate on the solution of some antimony-acid.

The other deposits of antimony ores occurring in association with limestones, especially those of the sulphide stibnite, seem to be intimately connected with, and dependent on, igneous intrusions, and it is doubtful whether they should be referred to the metasomatic or to allied hydatogenetic deposits.

METASOMATIC MANGANESE DEPOSITS.

Manganese is a metal very similar to iron in its chemical properties, and it occurs associated in varying quantities with most iron ores, either as carbonate,

or anhydrous and hydrated oxides. As regards formation, the ores of manganese are identical with those of iron, being deposited from similar solutions by the action of the same reagents.

In some of the metasomatic iron deposits mentioned previously, manganese occurs as the carbonate dialogite, the oxide pyrolusite and its products of hydration, according as the corresponding iron compounds exist as chalybite, hæmatite, or limonite.

In North Wales, manganese ores of metasomatic origin are associated with the chemically similar metals iron, nickel, and cobalt, in the Flintshire lodes (p. 252).

On the Continent, in the Odenwald, manganese deposits are met with in the Permian (Zechstein) dolomites; and noted masses exist in the Pyrenees, in the Cabesse district, associated with the Lower Carboniferous Limestone Series.

The Lower Carboniferous Limestone, or the 'Marbre Griotte,' contains several masses of carbonate of manganese, which occur as replacements. The ore bodies in depth pass into grey manganese ore, dialogite, and, as is usual with metasomatic deposits, present no well-defined boundaries with the country-rock. One mass measures 197 feet in length, 164 feet in width, and has been worked to a depth of 230 feet.

In Italy, deposits of manganiferous hæmatite occur in the districts of Orbetello and Monte Argentaro, associated with Triassic or Permian limestones. The ores contain about 35 per cent. of iron and 18 per cent. of manganese, with a general absence of sulphur and phosphorus.

In the vicinity of Santiago, Cuba, deposits of man-

ganite, pyrolusite, braunite, and wad, are associated with jaspers, the whole being regarded as a replacement of calcareous sediments by means of alkaline, siliceous, and manganiferous solutions.

METASOMATIC GOLD DEPOSITS.

Owing to the strong attraction of ferrous compounds for oxygen, and their consequent reducing action, they are occasionally employed to precipitate the metals gold and palladium from their solutions. That such a reaction has taken place in Nature in beds rich in ferrous iron there can be little doubt, and has occasionally given rise to bedded auriferous deposits.

Well-marked gold-bearing horizons have lately been described from South Africa, and their mode of occurrence points conclusively to the metal having had a metasomatic origin.

In the central portion of the Lydenburg district of the Transvaal, auriferous horizons are met with, chiefly in the dolomitic series, which forms the middle division of the Transvaal System, and lies between the Pretoria Series above and the Black Reef Series below; but similar horizons also occur in the upper and lower series (see Fig. 58).

The auriferous horizons follow, with the greatest regularity, the strike of the associated beds, and have participated equally in all the folding and faulting that the district has undergone. It is therefore certain that the introduction of the metal was at a period previous to the faulting. Along the ore horizons there is ample indication of the former existence of iron pyrites in quantity, where it probably existed as an original precipitation. Subsequent oxidation has caused the ore to have

a honeycombed appearance, and the pyrites has been changed into oxide or carbonate, and partially removed by solution.

These gold-bearing masses occasionally show unaltered pyrites, which would be more likely to occur in depth, and have a yield of 9 to 13 dwt. of gold to the ton.

The metal was certainly deposited after the consolidation of the enclosing sedimentary rocks, for the ore-mass contains much silica in the form of vein quartz, which could not have been deposited contemporaneously by any known process.

The presence of the pyrites on these horizons, or numerous pseudomorphs, suggests that this mineral played a part in the precipitation of the gold, and the abundant quartz points to the mineralizing solution being rich in silica.
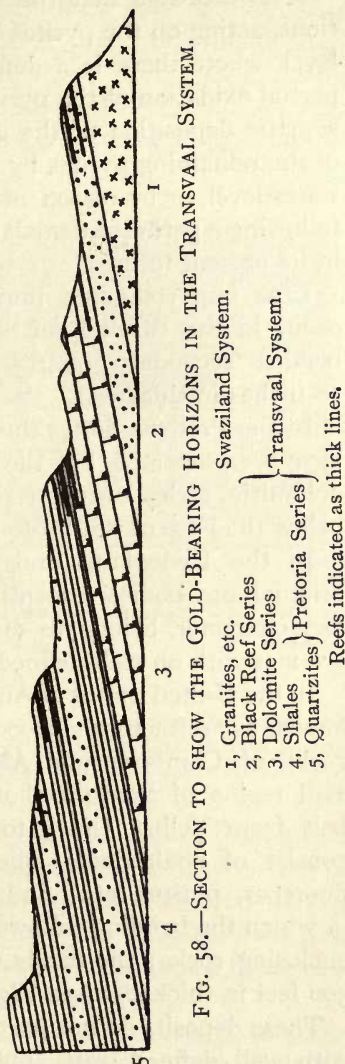
FIG. 58.—SECTION TO SHOW THE GOLD-BEARING HORIZONS IN THE TRANSVAAL SYSTEM.

Swaziland System.

1, Granites, etc.
2, Black Reef Series
3, Dolomite Series
4, Shales } Pretoria Series
5, Quartzites }

Transvaal System.

Reefs indicated as thick lines.

It is probable that the siliceous gold-bearing solutions, acting on the pyrites below the permanent water-level, where there is a deficiency of oxygen, caused a partial oxidation of the pyrites, and a consequent metasomatic deposition of the gold. Subsequent oxidation of the remaining pyrites by the lowering of the ground-water level, or by reason of its exposure at the surface following a period of denudation, has left the ore deposit in its present form.

Less important ore horizons of similar character occur in the Black Reef Series associated with inter-bedded secondary quartz veins ranging from 2 to 18 inches in thickness.

In the Pretoria Series three interbedded ore horizons have been detected, but the two important beds of the dolomitic series occur respectively 100 and 300 feet below the base of the Pretoria Series.

In the Lydenburg and Carolina districts, all the original ore bodies, excepting those of true sedimentary character, belong to distinctly bedded sheets, and are met with on well-defined and constant horizons.

In the United States of America, a number of deposits known as ' refractory siliceous ores ' are associated with rocks of Cambrian and Algonkian age, in the Black Hill region of South Dakota, and stretch as a broad belt from Yellow Creek to Squaw Creek. The ores consist of chalcedonic silica and quartz, with some fluorspar, pyrites, etc., and form flat banded masses, in which the banding follows the bedding planes of the enclosing rocks; the bands vary from a few inches to 300 feet in thickness (see Fig. 59).

These deposits do not partake of the nature of veins with well-defined walls, but they are associated with

beds of dolomite, into which they pass by insensible
gradations. They are evidently metasomatic in char-
acter, the solutions forming them having been intro-
duced down small and almost vertical fissures, on each
side of which the rocks have suffered considerable
silicification.
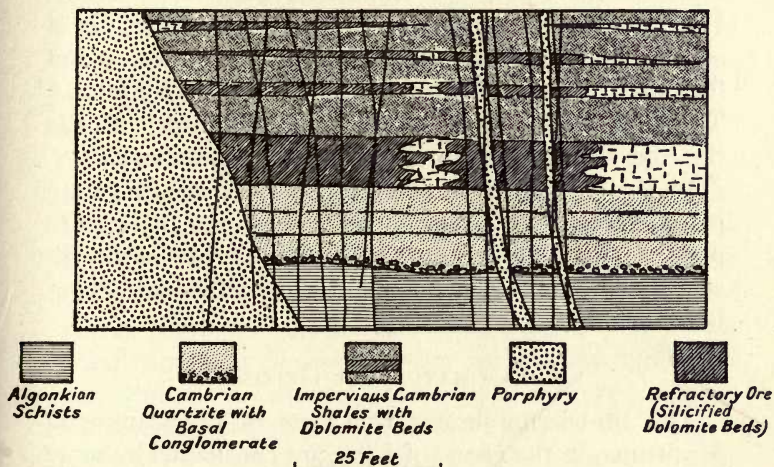
Fig. 59. — Diagram illustrating the Replacement of
Limestone Bands by Siliceous Gold Ore in the Black
Hills District, South Dakota. (After J. D. Irving.)

The chief mineral of the ore-mass, other than silica,
is pyrites, which on decomposition has given rise to
hæmatite and limonite, and caused a solution of the
adjoining limestone. Arsenopyrite, stibnite, fluorspar,
and gypsum, also occur, and there has been a formation
of brown mica.

These mineral masses compare in certain respects
with the ores of the Lydenburg district described above.

It is obvious that the mineralizing solution was alkaline and highly siliceous. The gold, which exists either native or as the telluride, has been introduced into these deposits by the same set of fissures, and has been deposited from its solution through the influence of some base in the country-rock.

In the Carboniferous Limestone plateau of Crown Hill, also in Dakota, gold and silver ores occur in a similar manner, associated with secondary silica and fluorspar, as metasomatic replacements of the limestone. The precious metals probably exist as tellurides, as was the case with the Cambrian ores mentioned above.

In the Lydenburg district of South Africa, the state in which the gold occurs is not known, and it is quite possible that it may be in the form of telluride, although so far there has been no mention of tellurium having been detected.

METASOMATIC TIN DEPOSITS.

The tin-bearing brown iron ores of the Campiglia Marittima, in the island of Elba, are considered by some to be of metasomatic origin. Their true nature, however, is still a matter for speculation, and it is quite possible that their occurrence may be due to some process other than metasomasis.

Instances of the metasomatic replacement of quartzite by cassiterite and tourmaline have been described from the Rooiberg district, Transvaal. The replacements are believed to have been effected by hydrothermal solutions connected with the pegmatites described on p. 55, and are therefore of exceptional interest. The sedimentary formation in which the deposits are found consists of alternating beds of

quartzites and shales believed to belong to the Pretoria Series (Upper Devonian). The quartzite bands, varying from a few inches to 2 feet in thickness, are extensively tourmalinized for many feet on either side of the veins, and are replaced by secondary quartz, felspar, mica, carbonate of iron, calcite, and, not uncommonly, cassiterite. The quartzite, consisting of quartz and felspar, is seen under the microscope to have both its principal constituents replaced by the minerals mentioned.

METASOMATIC URANIUM AND VANADIUM DEPOSITS.

In Utah, on the margin of the Green River basin, the Mesozoic sediments are penetrated and turned up by the laccolitic intrusions of the La Sal group on the east, the Abajo on the south-east, the Henry Mountains on the south-west, and San Rafael on the west. Near these intrusions the sedimentary rocks carry high-grade vanadium ores with some carnotite. The ores occur in sandstones, and are supposed to be due to the replacement of these rocks which have been acted upon through the agency of metalliferous solutions.

The vanadium compounds are the chief minerals present, including the vanadio - arsenides of copper, barium, and calcium. They occur in small crystalline aggregates or in radiating masses and sheaves.

In Southern Colorado, vanadiferous pitchblende is found in Jurassic sandstones. The minerals carnotite (used as a pigment by the Indians) and roscoelite occur exclusively in the La Plata Sandstones (Jurassic); there are two theories to explain their origin. The minerals were either dissolved by sulphuric acid or acid sulphates derived from the decomposition of pyritic minerals and

deposited in the sandstone, which somehow acted as a precipitant, or there were original vanadium and uranium minerals in the sandstone, which were subsequently decomposed.

Although uranium is generally derived from acid and vanadium from the basic rocks, the important mineral carnotite contains both these elements.

CHAPTER VI

BEDDED ORES DUE TO PRECIPITATION

By precipitation is meant the process by which certain constituents of a solution are thrown out of that solution in a solid form ; and in all cases it is dependent on the liquid being in a state of supersaturation with regard to the substance undergoing precipitation.

The precipitated ore deposits of this class may be divided into two groups. The first embraces all those minerals which are precipitated from solutions in which they existed as the same, or approximately the same, chemical compound.

The second includes those minerals which are the result of the addition of a substance which reacts with some salt of a metal in solution, forming a compound in respect to which the solution is in a supersaturated state.

We know from laboratory experiments that precipitation from a solution can be produced in a variety of ways, such as by lowering the temperature, by the evaporation of the solvent or its removal by some other means, and by the addition of some substance which forms with the metal in solution a salt with a less degree of solubility.

The concentration of a solution, and the consequent precipitation of its contents by a fall in temperature,

does certainly occur in Nature in the case of rising thermal waters ; but, generally speaking, such a process giving rise to bedded ore-masses is of rare occurrence. The deposition of the metallic ores is more often due to supersaturation caused by the evaporation of the solvent or the reaction of the solvent with some substance, either solid or liquid, with which it happens to come in contact. Most common of all, however, is the precipitation brought about when salts of certain metals are converted into different and less soluble compounds, either by the action of some other salt in solution or by the absorption of oxygen.

To take examples, let us consider the precipitation of certain carbonates, sulphides, and oxides.

Several metalliferous carbonates, such as those of iron and manganese, are held in solution by water charged with carbon dioxide, their solubility in pure water being small. On the extraction of the carbon dioxide from an aqueous solution of such salts, ferrous and manganous carbonate will be precipitated if oxidation is prevented. Such a reaction may give rise to bedded deposits of these compounds, and at the same time is the cause of the stalactitic and stalagmitic ores of iron and manganese, although these have most often undergone more or less complete oxidation. To take examples of another type, the sulphides of copper and lead will be precipitated from aqueous solutions of their sulphates on the reduction of these salts by organic matter or by the action of sulphuretted hydrogen on their soluble salts in an acid solution. In the case of oxides, a common form of precipitation is that of ferric oxide and ferric hydrate from solutions of ferrous carbonate which are absorbing oxygen from the air. Magnetite is

occasionally found as the result of incomplete oxidation of ferrous solutions, and is probably formed by the interaction of ferrous and ferric salts in the presence of an alkali.

Ocean water, which generally has a slight alkaline reaction, contains small quantities of almost every metal in solution, and is undoubtedly the most common source of the metallic minerals existing as precipitates in marine and esturine sediments.

The waters of inland seas, however, are often acid in reaction, and the minerals precipitated from these are in some measure different from those found in ordinary marine sediments. To illustrate this difference most clearly, it is only necessary to contrast the Mesozoic precipitated iron ores with the Permian and Triassic rock-salt and gypsum deposits.

Precipitated bedded ores may occur in two ways— either as continuous sheets intercalated between non-metalliferous sediments, or as crystals, grains, or nodules, scattered through the beds. As examples of continuous sheets, we may mention some of the clay ironstones occurring in the Coal-Measures of so many districts; and in illustration of the second class we may cite the impregnation of shales with metallic sulphides, and sandstones with such compounds as carbonate of copper.

There is sometimes the greatest difficulty in deciding whether certain ore deposits should be regarded as true precipitations or as metasomatic replacements of the country-rock. The mode of occurrence will at times afford a distinct clue as to their origin, as also will the accompanying minerals. But a more or less characteristic feature of precipitations is their exact parallelism

with the bedding of the enclosing rock, and their recurrence at more or less frequent intervals on slightly different horizons. The upper and lower limits of such ore-masses are most often clearly defined, and do not shade imperceptibly into the adjoining barren rock, as do the metasomatic deposits previously described. In the case of the impregnations of unmetamorphosed shales and sandstones with minute patches of ore material, it is obvious that the ores could have been formed by no process other than precipitation, possibly helped subsequently by the process of concretion.

PRECIPITATION AS OXIDES.

IRON AND MANGANESE.

The chief deposits of oxide of iron which owe their origin to direct precipitation are those occurring as lake or bog iron-ore.

The iron is thrown out of solution as a mixture of hydrated oxides by the agency of algæ and bacteria, which have the property of extracting iron from solutions of its carbonate and sulphates.

Ferric hydrate may, of course, be deposited from iron solutions by the simple process of oxidation, as in the case of the carbonate—

$$4FeCO_3 + O_2 + 3H_2O = Fe_2(OH)_6 + Fe_2O_3 + 4CO_2,$$
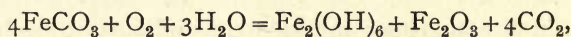
or by the action of some salt of an organic acid, such as ammonium humate, on a ferrous solution (*e.g.*, bicarbonate of iron).

Deposits of ferric oxides of sedimentary character are well known in many districts, amongst which we may mention those of Lusace, Silesia, Banat, Jutland, etc.

The lakes of Scandinavia, however, especially in the provinces of Småland, Vestragoethland, and Dalarne, offer some of the best examples, and are most instructive, seeing that the actual formation of the ore can be watched and studied.

In the Scandinavian lakes the precipitation is brought about chiefly by fresh-water algæ, to which the names *Leptothrix ochracea, Gallionella ferruginea*, etc., have been given, and the iron is thrown down entirely as hydrated oxide. The alga *Gallionella* flourishes at a distance of about 10 or 12 yards from the shore, and to a depth of 30 feet below the surface of the water. The ore deposit consists of a slimy mass of hydrated iron oxides and gelatinous silica, and ranges from a few inches up to $1\frac{1}{2}$ feet in thickness.

After a time a concretionary process begins to act within the unconsolidated mass, with the formation of oolitic or pisolitic granules—a feature which is most instructive and helpful when considering the origin of some of the pisolitic iron ores associated with the Mesozoic and Tertiary sedimentary rocks.

The Swedish lake deposits are worked even when only a few inches thick, and it is interesting to note, with regard to the rate of formation of these ores, that they renew themselves in a period of from fifteen to thirty years.

It has already been mentioned that magnetite is a mineral rarely to be accounted for by original deposition from solution. There are, however, certain iron ore beds which contain this mineral in some quantity, and in which it was evidently deposited by the agency of water under normal conditions. The occurrence of such deposits as the magnetic ore of Rosedale, in York-

shire, and the magnetite in the hydrated ores of the Rhine provinces, is a difficult thing to explain. It must, however, be borne in mind that a magnetic hydrated oxide of iron, with the composition $FeO,Fe_2O_3xH_2O$, can be made artificially by treating a ferrous salt with a soluble ferric compound in the presence of an alkali. Here, however, as in the case of the carbonate of zinc, there seems a tendency in Nature to form the anhydrous compound if possible. It may be that the slowness with which the reaction takes place in Nature is a controlling factor, or it may be that the loss of water is governed by the shrinkage of the mass under pressure. The value of the bog iron ores is greatly diminished by their relatively high percentage of phosphoric acid.

Manganese deposits occur either alone or in association with iron compounds. We get bog-manganese similar to bog-iron; and the bedded oxides, psilomelane etc., have an identical origin with limonite and the other hydrated oxides of iron.

With regard to the source of these metals, what was said with reference to the solutions which gave rise to metasomatic replacements is equally true for the iron and manganese precipitations.

The iron was derived chiefly from the ferromagnesian silicates of igneous rocks and from the pyrites of sediments, decomposing under the influence of carbon dioxide, alkaline carbonates, and vegetable acids, or by partial oxidation. The source of the manganese, also, lay chiefly in the ferromagnesian silicates, many of which contain this metal in some quantity. Manganese most often seems to have been carried in acid solutions rich in silica, the precipitation of the oxides generally

depending on the reaction of the manganese salt with some base in the solution. The oxides may, however, be thrown down, as in the case of the oxides of iron, by the oxidation of the carbonate and by the loss of carbon dioxide from the solution.

In an acid solution of salts of iron and manganese, the addition of a base first precipitates the sesquioxide of iron, which is followed by the protoxide and dioxide of iron and manganese. It thus appears that the last portion to be precipitated will be the richest in manganese, a suggestion borne out by a study of natural deposits.

The deposits of oxides and hydrated oxides of iron and manganese, which appear to be of the same age as the sediments which enclose them, are fairly numerous, and from most of these the general characters of metasomatic deposits are absent, except in so far as they have been affected by secondary changes.

At the same time, it is not always possible to say definitely that they were deposited as oxides, and not as carbonates which have subsequently undergone oxidation. The manganese deposits of Merionethshire, for instance, consist of oxide near the surface, but in depth are found to pass gradually into carbonate.

In this case the change to oxide is quite secondary, and the true nature of the deposit would not have been detected in shallow workings. It must always be borne in mind that bedded masses of oxides, of either iron or manganese, are liable to pass into the carbonates of these metals when followed into ground which has not been exposed to the weathering influence of oxygenated waters.

In England and Wales examples of bedded precipi-

tates may be cited from several districts and several geological horizons. Iron ores occur in the Oolites of Rosedale in Yorkshire, in the Corallian of Westbury in Wiltshire, and Abbotsbury, in Dorsetshire, and in the Lower Cretaceous of the East of England. The ores are mostly oolitic or pisolitic in character, and consist chiefly of hydrated oxides, with a small proportion of carbonate. The Rosedale deposit has the somewhat unusual feature of being magnetic, but in this respect is similar to some of the oolitic brown ores of France and the Rhine provinces, which also occur in the Middle Jurassic strata.

In Europe some of the ferriferous deposits, like those of the Lias, Inferior Oolite, and Lower Cretaceous, seem to be due in part to original precipitation, and partly to metasomatic replacement. The pisolitic ores especially seem to have the characters of original sediments.

In the departments of Maine and Loire, hæmatite occurs interbedded with the Lower Palæozoic sediments.

The deposits of Calvados occupy a position above the Armorican Grits, and below the *Calymene*-Shales of the Ordovician System. They are about 6 feet in thickness, and consist of hæmatite and limonite with some carbonate.

An oolitic iron ore occurs in the synclinal area of Prague, in Bohemia, above the Przibram Quartzite. It contains some silica and a rather high percentage of phosphoric acid.

Similar ores, but still more impure, are found in Andalusia, associated with Lower Palæozoic sediments.

Amongst the deposits of later date we may mention the oolitic ores of the Wealden and Neocomian strata

of France, which are well displayed in the Bas-Boulonais and the district of Vassy respectively.

The ores in the Wealden deposits of Kent, associated with the Wadhurst Clay, seem to approximate most closely to a clay ironstone, and thus present characters which would group them with the bedded hydrous carbonates of the Coal-Measures, to be subsequently described.

Brown iron ore of oolitic character forms a bed 30 to 50 feet thick in the Tertiary deposits of the Ketch Peninsula in Russia, It yields 38 to 42 per cent. of iron, and 2 to 4 per cent. of manganese. At the same time it has an exceptionally low percentage of phosphoric acid.

Amongst recent deposits the fresh-water bog-iron ores are the most important. They occur, in all north temperate regions, where ferruginous waters are more or less stagnant in shallow depressions of the surface, and kept at a more or less constant level owing to the impermeability of the subsoil.

Such deposits are extremely prevalent in the lowlands of North Europe. They are found in Southern Scandinavia, in the low-lying country of Holland, on the drift plain of Northern Germany, in Poland, and Russia.

In the British Isles, bog-iron ores occur in several districts in Ireland in the central plain, and in the Shetland Isles. They contain a variable quantity of ferric oxide, ranging from 20 to 78 per cent. in different grades of ore. All these precipitated oxides of iron and manganese are associated with a good deal of phosphoric acid, sometimes as much as 9 or 10 per cent., a feature which detracts seriously from their value.

The precipitates of oxide of manganese in the form of pyrolusite the anhydrous oxide, psilomelane the hydroxide, manganite, and the earthy hydrated varieties generally styled 'wad,' are common, but not so widely distributed as the equivalent ferruginous compounds. Manganese in small quantities is associated with almost every aqueous deposit of iron ore, but its percentage occasionally rises in excess of the iron, giving rise to true manganese deposits. Nodules of manganese ore are well known in recent deep-sea accumulations.

On the Continent, some of the ores of Nassau and Westphalia are undoubtedly original sediments, but their character has been more or less completely changed by secondary local enrichments and by metasomatic replacements of the country-rock.

As in the case of the iron ores, it is in the oolitic deposits that we have the clearest evidence of contemporaneous formation of manganese ores.

In Spain and in the Caucasus, deposits of oolitic character are well known. The Caucasus ores belong to the Eocene or Miocene; they occur in the Kvirila Valley in a series of beds of sand and sandstone resting on the Cretaceous limestones. The similar Miocene deposits of Spain occur, amongst other places, in the Val de Peñas, in the province of Ciudad Real.

The chief ores of the United States of America are those located along the border of the Appalachian region, in the States of Virginia, Georgia, and Arkansas. They occur above the Potsdam Sandstone of Lower Palæozoic age, and, although now existing chiefly in the form of oxides, were probably deposited in the first instance as carbonate. The manganese originally existed in a series of limestones and shales, over-

ying the Potsdam Sandstone, in which it had been deposited either as a precipitate or as a metasomatic replacement. On the destruction of these beds a residual clay was formed, and in this clay much of the ore remained as concretionary masses of oxides of manganese, such as pyrolusite and psilomelane.

Extensive limonite deposits are associated with the manganese, and have been derived from the beds above the Potsdam Sandstone in a similar manner. It is difficult to place these ores in any particular class, but it is best, perhaps, to regard them as precipitations.

Bog-manganese has an identical origin to that of bog-iron, with which it is usually associated; it is presumably extracted by organic agencies from solutions of the carbonate in water containing an excess of carbon dioxide, and is precipitated, like the corresponding iron ore, as a mixture of hydrated oxides.

COPPER.

Oxides of copper occur in the copper-bearing sandstones of the province of Perm, and in Northern Bohemia. It is, however, quite possible that they were not deposited as such, and are merely alteration-products from copper pyrites. In Russia the copper ores occur in the Rothliegende division of the Permian System, sometimes as oxides, and sometimes as sulphides, carbonates, and even as the native metal. Metallic copper may in such cases be regarded as the latest stage in the reduction of secondary products formed by the oxidation of some such compound as the sulphide. The beds with which these ores are associated are generally full of plant remains, and it is supposed the organic matter acted as the precipitant.

The beds are, for the most part, almost horizontal. Their ore-bearing layers are thin, ranging from about 2 inches to 2 feet in thickness, and yielding a variable quantity of copper.

It is quite possible that these oxides may be original precipitations; but at the same time, chemically considered, it is more probable that they have been derived from the sulphides by a subsequent process of oxidation.

The red and black oxides of copper are often met with in the upper and oxidized part of lodes which carry copper pyrites (p. 369).

ALUMINA AS BAUXITE.

Chemical deposits of bauxite which appear to be independent of metasomatic action occur in several districts in Europe and the United States. They seem to have originated from igneous masses by the process of weathering, and to be derived largely from the felspathic ingredients of these rocks.

The first stage is the formation of the aluminium silicate, which subsequently, under the influence of alkaline carbonates in solution, parts with its silica and deposits hydrated aluminium oxide.

The chemical nature of these deposits is clearly indicated by their pisolitic and concretionary structure, the spherules occasionally reaching 1 inch in diameter.

The bauxite deposits of Arkansas, in North America, have been well described, and their mode of occurrence is well known.

Arkansas is a district which may be roughly divided into two by a north-easterly and south-westerly line separating the Older Palæozoic rocks of the north-west

of the State from the Tertiary and Recent deposits of the south-east. The Palæozoic rocks, consisting chiefly of limestones and shales, have been folded, and subsequently to the folding intruded by masses of normal and elæolite syenite.

The bauxite forms a more or less continuous sheet over the surface of these igneous masses, and extends beyond them on the plane of denudation. It is evident that they had their origin in a mass of syenitic detritus, and were formed before the deposition of the Tertiary sediments.

It will be seen from the above that the bauxite deposits occupy the position of a great unconformity—in other words, occur on a surface which was undergoing denudation for a considerable period.

In South Europe, along the coastal country of the Mediterranean, pisolitic bauxite deposits of considerable extent occur in a similar position. They rest indiscriminately on beds ranging from the Rhætic in Hérault to the Gault at Reveset, and are overlain by the Cenomanian Hippurite Limestone, and by fresh-water deposits of Danian age.

In the Auvergne, bauxite occurs as a covering of gneissose rocks, and has probably had a similar origin to the deposits of Arkansas.

Certain deposits associated with basalts (p. 264) are supposed by some to have had a metasomatic origin. Their mode of formation, however, is still unsatisfactorily explained, and they may quite possibly prove to belong to the above class.

Bauxite deposits of great thickness, ranging up to 12 feet, occur in the Wochein district of Austria; and they have also been worked in Piedmont.

Precipitations as Carbonates.

IRON AND MANGANESE.

The carbonates of iron and manganese are occasionally found associated with sediments in a manner that points clearly to their having been deposited by chemical means, contemporaneously with the enclosing rock. They form well-defined layers parallel to the stratification planes of the beds in which they occur; and there is no evidence of metasomatic replacement of the country-rock, except, perhaps, in certain secondary enrichments of the mass by subsequent solution and redeposition of the ores. Iron, manganese, and magnesium form similar carbonates in which any one of these metals may partially replace another.

The carbonates of iron and manganese are soluble to some extent in water containing an excess of carbon dioxide, and where oxidation is prevented by the presence of some reducing agent, such as decaying vegetable matter. Such solutions, on undergoing a certain amount of concentration and loss of carbon dioxide, would deposit the metals as carbonates.

Salts of iron and manganese existing in the ferric and manganic states, under the influence of decomposing organic matter would be reduced to the corresponding ferrous and manganous compounds, and the addition of an alkaline carbonate would produce the spontaneous precipitation of the hydrous carbonates of the metals. It is most probable that the alkaline carbonates have played a very important part in the precipitation of the clay ironstones described below, but many of the manganese deposits are best explained

as precipitates from solutions of the carbonate on the loss of carbon dioxide.

It is obvious, in the case of these deposits, that reducing agents must have been at work at the time of their precipitation, for, failing that, the metals would have been deposited as oxides or hydrates; and in this connection it is interesting to note that the bedded deposits of precipitated carbonates are almost always associated with carbonaceous strata, such as the black shales of the Ordovician and Silurian or the plant-bearing shales of the Carboniferous.

The most important group of precipitated iron ores occurs in the productive Coal-Measures of a large portion of the northern hemisphere—in the British Isles, the Ruhr basin of Westphalia, North America and China. These spathic or argillaceous ores are not particularly rich; they consist of an impure hydrated ferrous carbonate, and contain only 30 to 35 per cent. of metallic iron, the average of several districts being 33. The impurities consist of silica, alumina, and lime compounds; but the percentage of phosphoric acid seldom rises above 1·0, a feature which in a measure compensates for the comparative leanness of the ore.

The masses of ironstone occur in two ways, either as continuous sheets or as bands of concretionary masses running parallel to the bedding; both types, however, have had an identical mode of origin.

In the British Isles, deposits of spathic iron ore occur interbedded with the Coal-Measures in South Wales, Shropshire, North and South Staffordshire, Derbyshire, Northumberland, Durham, and the South of Scotland; North Staffordshire being the most important district, and having the greatest yield.

The North Staffordshire ores are dark brown to black compact masses, varying from a few inches to 2 feet in thickness. They invariably overlie a seam of coal, the thickness of the ore varying inversely as the thickness of the latter. Compared with similar deposits of other districts, they are richer, the percentage of iron being given as—ferrous oxide, 40 to 46 per cent.; ferric oxide, 4 to 15 per cent.

In all districts other than North Staffordshire it is extremely difficult to trace any connection between the beds of ironstone and the coal-seams, but that they had an identical mode of formation in all cases there can be no doubt. They were evidently deposited as a ferruginous mud, which has subsequently undergone much dehydration and contraction. In some of the concretions (sphæro-siderite) an organism, such as a portion of a plant or animal, has acted as a nucleus, and the evidence of contraction is furnished by many cracks and cavities now filled with calcite or quartz.

Almost all the spathic ores contain some manganese which also exists as carbonate, and would have been precipitated simultaneously with the corresponding iron compound.

In Coal-Measure-times it is probable that the surface waters were richer in mineral matter than at almost any other period. The dense vegetation would give rise to humic acids in great quantity, and, as is well known, these acids, from the ease with which they oxidize, are some of the most powerful natural solvents.

On the Continent, deposits of exactly similar nature and mode of occurrence are associated with the Upper Carboniferous rocks of the Ruhr basin in Westphalia, in the neighbourhood of Essen and Hörde; in the

lower part of the Coal-Measures in the basin of Saar-
bruch, in Upper Silesia; and in the basin of the Loire,
in France.

Identical clay ironstones occur in the productive
Coal-Measures of the United States of America, espe-
cially in the eastern State of Pennsylvania and in the
Appalachian region. Spathic ores are also met with in
Nova Scotia.

In deposits of later date, ore-masses of this character
are occasionally met with—as, for instance, in the
Keuper and Jura of Upper Silesia. In England an
example may be cited from the Lower Cretaceous beds
of the Weald, in Kent.

With regard to the deposits of carbonate of man-
ganese, it is not so easy to put forward trustworthy
examples. In our own country, the best, perhaps, is
that of Merionethshire, where, in the neighbourhood of
Barmouth, manganese carbonate occurs on two distinct
horizons: one just above, and the other just below, the
grits, which form a well-marked series in the lower part
of the Cambrian System.

The ores have been extensively mined all along the
line of outcrop in a series of shallow workings. They
were presumably deposited from solution as carbonates,
and as such they occur in depth; but near the surface
they have passed into various hydrated oxides in the
process of weathering.

Manganese carbonate, as an original deposit, exists as
layers in the Devonian beds of the Pyrenees, in the
Oligocene of Mähren, and at a few other localities in
Europe.

Besides the deposits of almost pure manganese car-
bonate, such as those mentioned above, almost all the

~	Alluvium.		Moelfre Grits.
:.:	Blown Sand.		Mudstones.
	Menevian & Lingula Flags.		Harlech Grits

Manganese beds indicated by thick black line.
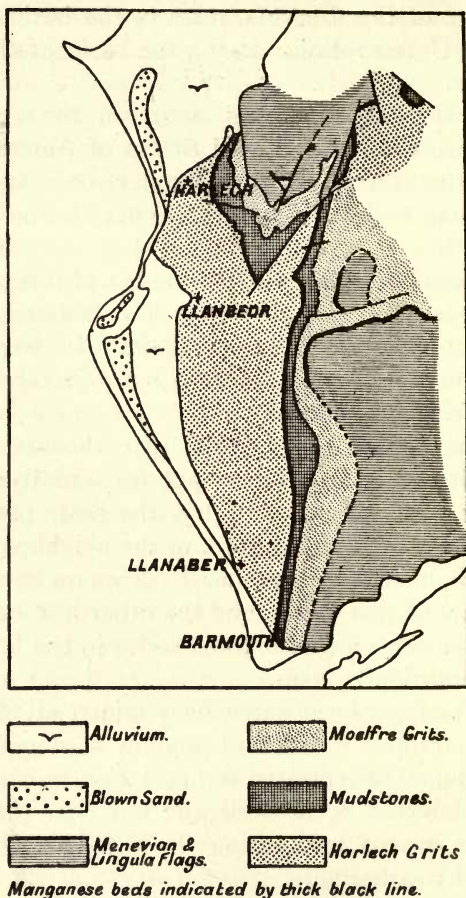
FIG. 60.—MAP SHOWING THE MANGANESE-BEARING HORIZONS IN THE CAMBRIAN ROCKS OF MERIONETHSHIRE, NORTH WALES. (AFTER GOODCHILD.)

Scale, 4 miles to 1 inch.

bedded masses of carbonate of iron contain a certain amount of manganese in a similar state. In these cases

it often exists as a double carbonate of iron and man-
ganese—$(Fe,Mn)CO_3$.

The deposits of Franklin Furnace are probably meta-
morphic in character (p. 343).

COPPER.

Copper carbonate in the form of the blue azurite or
chessylite, or the green malachite, is occasionally found
as thin beds, impregnations, and concretions, in sedi-
mentary rocks. In these rocks its origin is probably
due either to direct precipitation or to the alteration of
copper pyrites which was itself an original precipitate.

The two basic cupric carbonates, azurite and mala-
chite, have been worked in the red Triassic rocks of
Britain—in Somersetshire, on the north-east margin of
the Quantock Hills, near Doddington, and also near
Bridgewater—associated with brown iron ore.

In Cheshire, also in rocks of the same age, they
occur in the sandstones of Alderley Edge.

There is, however, no occurrence which can be defi-
nitely proved to be an original precipitate of carbonate.
The Doddington deposits are clearly due to alterations
of pyrites, for unchanged pyrites is occasionally met
with.   In the same way the other ores of Somersetshire
and Cheshire may be similarly accounted for.

Similar deposits of the carbonates of lead and zinc
have had their origin in galena and zincblende.

Precipitation as Sulphides.

The bedded deposits of sulphidic ores which owe their
origin to true chemical precipitation, and are more or
less independent of metasomatic processes, are given

rise to either by the action of sulphuretted hydrogen on metallic solutions or by the reduction of soluble sulphates.

The metals which most often exist as sulphides, occasionally with some arsenic, are those of iron, copper, lead, and zinc, with sometimes nickel, cobalt, silver, and antimony. The ore occurs either as impregnations of some sedimentary rock, in which it is finely disseminated as crystals or grains, or as more or less continuous bands intercallated between two less metalliferous layers. Occasionally the place of a continuous sheet of ore is taken by a layer of concretionary nodules.

The origin of the metallic solutions has already been touched upon, but the cause of the precipitation is not so obvious. There seems, however, to be two more or less distinct ways in which the deposition may be produced.

As was pointed out in the case of the oxides, many organisms living in water are capable of decomposing sulphates, with the liberation of sulphuretted hydrogen. This gas, acting on the metallic solutions, will account in a measure for much of the pyrites disseminated throughout a variety of deposits, such as the Oxford and Kimmeridge clay. At the same time the pyrites of many of the shales, slates, and clays, is evidently to be accounted for by the direct reducing-action of decaying organic matter, either vegetable or animal, and as a proof we find pyrites replacing the soft parts of fossils in sedimentary deposits of almost every age. Pyrites replaces graptolites in the Ordovician and Silurian Systems, plants in the Coal-Measures, mollusca in the Mesozoic rocks, and in recent times impregnates the timber of old mine levels, all changes brought about

by the reducing agencies of organic compounds. Many clays which now contain sulphides most sparingly can be proved to have previously held them in much greater quantity. The London and Kimmeridge clays, for instance, are full of gypsum in large crystals, which have been formed by the action of sulphuric acid, arising from the oxidation of pyrites, on the calcareous tests of organisms. In a non-calcareous clay the oxidation of pyrites will take place with the formation of alum shales.

There are a few additional points in connection with the precipitation of sulphides which are of interest. In the above list of metals it will be seen that there are two classes included—one containing the metals iron, nickel, cobalt, and zinc, which are usually only precipitated as sulphides from alkaline solutions, whilst the others may be thrown down from acid solutions of their salts.

In the presence of organic acids, however, and under increased pressure, it must be remembered that the general rules of precipitation have many exceptions, and that organic acids undoubtedly play a most important part in Nature both in the solution of the metals in the first instance, and in governing their subsequent precipitation.

To take examples, nickel and cobalt are precipitated as sulphides by the action of sulphuretted hydrogen on their soluble salts of organic acids in the presence of these acids in a free state. Zinc sulphide, on the other hand, may be precipitated from a feebly acid solution under increased pressure.

Manganese sulphide is rarely found in Nature, for it is one of the most soluble compounds of this class; it

is only precipitated in the presence of alkalies, and its precipitation is thus completely prevented by the presence of free weak acids. Manganese as sulphide does occur, however, in combination with the sulphides of other metals.

Copper and lead form soluble, and at the same time stable, salts with hydroxy organic compounds, which, although resisting the action of many of the usual precipitants, are readily decomposed by sulphuretted hydrogen, the metals separating out as sulphides. The ease with which almost insoluble metallic salts pass into solution in the presence of certain organic compounds is exemplified by the case of lead sulphate, which is practically insoluble in water, but is readily dissolved by a solution of ammonium tartrate.

Turning again to the natural deposits of sulphides, and considering the metals which occur together, we are constantly met by a certain amount of conflicting evidence, whether we consider the solution from which they are deposited to have been acid or alkaline in reaction, and it is almost impossible to form any definite conclusion as to the true nature of the solution.

There is no reason for supposing, however, that all deposits of sulphides have been derived from one type of solution, and it is even possible that at a considerable depth the lowest stratum of a sheet of water, owing to slow diffusion, might have a different reaction from the main mass.

Taking into consideration a large number of cases, it seems most reasonable to favour the idea that the precipitation of sulphides has chiefly taken place from slightly acid or neutral solutions through the agency of sulphuretted hydrogen liberated by living organisms, or

through the direct reduction of the sulphates of the metals by decaying vegetable or animal matter.

In the case of iron pyrites it is extremely difficult to suggest the exact method of its precipitation, for, unlike some of the other sulphides, it cannot be artificially precipitated from solutions of iron salts. There is, however, no doubt that it can be formed from solutions of the sulphates at normal temperature and pressure, as is shown by the impregnation of mine-timber by this mineral.

IRON AS IRON PYRITES.

Pyrites, in the British Isles, is found associated with both marine and brackish water sediments of almost every age. It occurs finely disseminated through shales and clays, as nodules occasionally reaching considerable dimensions, and less frequently as well-defined beds. It is in the Coal-Measure shales that we meet with its strongest development, and where it often forms layers of considerable thickness. Associated with coal-seams in South Wales and other coal districts, it gives a distinctive character to certain seams, and gives rise to such names as the Brass Vein, Fiery Vein, etc.

In the Coal-Measures the pyrites deposits are almost certainly due to the reduction of sulphate solutions by decomposing vegetable matter, but at the same time it is obvious that a good deal of pyrites has been formed along fissures and joints subsequently to the consolidation of the coal-seams. This is probably only a secondary change, and is due to the migration of pyrites by solution and redeposition. Much pyrites is contained in some of the Ordovician graptolitic shales, in the Oxford Clay of the southern and eastern counties, and

in the Tertiary deposits, while nodules of a concretionary character are abundant in certain zones of the Chalk.

On the Continent, the most famous deposits are those of Rammelsberg, in the Northern Harz Mountains, occurring in rocks of Middle Devonian age.   They form layers up to 15 yards in thickness, parallel to the bedding of the enclosing rocks; but the whole sedimentary series has undergone extensive plication.   The ore consists of a mixture of sulphides, including pyrites, copper pyrites, zincblende, and galena, with a certain amount of barytes.   These ores, however, are by some regarded as of secondary origin.

An almost equally important district is that of Meggen, in Southern Westphalia, where the ore is also associated with deposits of Devonian age.   It occurs between the lower shales of the Upper Devonian (Lenne Shales) and the Middle Devonian limestone-group.

As at Rammelsberg, it contains other sulphides, such as zincblende, etc., and accessory barytes.   Analyses show about 35 per cent. of iron and 44 per cent. of sulphur, some zinc, but little or no copper and lead.

In both the cases cited above, although a metasomatic origin has been claimed for the ores, their bedded character, their association with bituminous material, their oolitic structure, as well as the presence of pyrites concretions in the neighbouring beds, point more or less clearly to their having had a sedimentary origin. Iron pyrites also occurs in abundance associated with the Tertiary brown coals of Germany.

COPPER AS COPPER PYRITES.

Copper pyrites as a mineral of sedimentary origin is of wide distribution, existing not only on many

geological horizons, but in widely separated districts. One horizon, however, more than all others in Europe, is famous for its copper deposits—namely, that of the so-called ' Kupferschiefer.'

The Kupferschiefer are bituminous shales and sandstones of Permian age, and form a central member of the Lower Zechstein, lying between the Zechstein Limestone above and the Zechstein Conglomerate below, which rests unconformably on older Palæozoic rocks. The Kupferschiefer are remarkable, also, for their richness in animal remains, chiefly fish, and their constant characters over wide areas; their marine origin is clearly demonstrated by the presence of such fossils as brachiopods and echinoids.

The ore occurs as finely divided grains and crystals of small size; it consists chiefly of copper pyrites, but it contains also some galena and other sulphides. The most important mining district is that of Mansfeld, in the Lower Harz Mountains. The ore-layers are extremely thin—less than 2 feet in thickness—and the percentage of ore seldom rises above 3; but, at the same time, this district has had an annual yield of about 11,100 tons of copper, as well as a fair quantity of silver.

Although the Mansfeld district is now the only important area where the ores of the Zechstein are worked, the Kupferschiefer stretch into Hesse and Westphalia, and at one time were extensively mined at Riechelsdorf, Bieber, and near Saalfeld.

There is no doubt that these ores owe their origin to the reduction of metallic sulphates by means of decomposing animal and vegetable matter, of which there is such striking evidence.

In other countries similar deposits occur in North America on a similar horizon. In Texas, copper pyrites, locally altered by atmospheric agencies into malachite and azurite, occurs associated with bituminous material in the Wichita and Clear Fork beds, a series of deposits very like the Central European Zechstein in origin and appearance. There are three chief horizons —one in the Wichita beds, and the others in the Clear Fork group. Mention has already been made of the copper-bearing sandstones, such as those of Perm, Bohemia, the district between Aachen and Saralouis, and of Corocoro in Bolivia, where it is supposed that the ores were originally deposited as sulphides, although they now exist chiefly as oxides and carbonates. The idea of precipitation as sulphides is strengthened by the presence of bituminous matter and large quantities of sulphates, such as gypsum and barytes.

Yet another type of deposit, consisting essentially of the sulphides of copper, occurs associated with volcanic tuffs and breccias of andesitic composition. The Boleo district of Lower California offers us the best example. The district of Boleo is an elevated plateau dissected by deep valleys, along the sides of which outcrops a series of almost horizontal volcanic rocks, largely of a fragmental character. These beds of tuff and agglomerate, which may be classed with the andesitic and trachytic groups of volcanic rocks, contain several copper-bearing layers varying from 2 to 10 feet in thickness. There is no doubt that these beds were laid down under water, and it is more than probable that the ores are true precipitations. The metal exists as sulphide, but we also meet with large amounts of secondary compounds, such as the oxides, chloride (atacamite), silicate (chryso-

colla), and the basic carbonates. The sulphides, however, are always abundant below the level of percolating atmospheric waters. The gangue consists chiefly of argillaceous material, and it is interesting to note that to the north-east of the district thick accumulations of gypsum are found on the same horizon, showing that sulphates were undergoing considerable concentration in the waters from which the ores were precipitated.

Somewhat similar in mode of occurrence are the copper ores of the Southern Caucasus, where beds of copper pyrites are associated with quartz andesites and trachytes.

There are several districts where the ores have been exploited, the most important being those of Kedabek, Achthal, and Allahverdi. The ores occur in highly siliceous layers between the lava-flows, are associated with other sulphides, such as zincblende and galena, and are accompanied by considerable masses of sulphates, such as gypsum and barytes. As in other districts, alterations have given rise to oxides and carbonates, which occasionally occur to the exclusion of the pyrites.

SILVER, LEAD, AND ZINC.

Silver, lead, zinc, and a few other metals of less importance, occur as precipitated sulphides, either alone or combined in the mineral fahlore (tetrahedrite), which also contains copper. Fahlore, however, is more common in the true veins and those bedded ore-masses which have undergone a certain amount of metamorphism (p. 337).

In our own country, except for a few insignificant occurrences of zincblende and galena in the Mesozoic

clays, there are no examples of this class.   But where these two sulphides are met with, they always occur surrounding or replacing the soft parts of some organism.   As we have already seen, sulphides of these metals are associated with the copper ores of the Kupferschiefer of Central Europe, and were probably present to a considerable extent in the copper-bearing sandstones of Bolivia, St. Avold, and other districts— in fact, in most areas from which copper ores have been cited.

NICKEL AND COBALT AS PYRITES, ETC.

Nickeliferous and cobaltiferous pyrites, as well as the sulphide millerite, are occasionally met with in connection with other sulphidic ores.   In Britain these minerals have been noticed associated with the pyrites and spathic iron deposits of the Coal-Measures, while nickel and cobalt in an undetermined form have been shown to exist in the precipitated iron ores of other horizons.

GOLD IN SINTERS.

Gold in a native state occurs as precipitations in certain highly siliceous accumulations formed at the surface under hydrothermal conditions.   The gold is probably carried in solution by sulphate of iron, and on the decomposition of this compound, on reaching the surface, is deposited with the gelatinous silica and iron oxides.   A good example of such a deposit is that of Mount Morgan in Queensland, Australia, where a siliceous sinter impregnated with hæmatite yielded as much as 170 ounces of gold to the ton.   The district of Mount Morgan is largely composed of dioritic rocks associated with rhyolites.   The former, as we have seen,

are the chief original gold-carriers, and in this case also were probably the source of the metal.

Similar deposits, but of less economic value, occur in Nevada and in the Yellowstone Park. In both cases the sinter has been deposited from highly alkaline and siliceous water connected with rhyolitic rocks, which form a feature of these districts.

It must be born in mind that some of the so-called quartz-reefs occurring amongst the older rocks might have been given rise to by a similar process.

Precipitation as Silicates.

Occasionally the metals, iron, manganese, and zinc, are precipitated in the form of silicates from aqueous solutions, but this class of deposit is, as a rule, of no great importance. We have seen that many metalliferous silicates associated with metasomatic deposits are really of a secondary character, and result from the alteration of other metallic compounds by alkaline siliceous waters. There are, however, cases where silicates may exist as original precipitations. They are probably derived directly from igneous rocks, passing into solution during the process of weathering. They were deposited, as was the case with the oxides and carbonates of iron and manganese, as more or less spherical grains or as continuous sheets, the precipitation being largely brought about by the loss of carbon dioxide from the solution and the neutralization of the alkaline carbonates.

Iron in the form of silicate has been precipitated in the Huronian Series of the Lake Superior region, in the Mesabi district. The silicate has been called greenalite, and occurs as pale green grains, having an appear-

ance and mode of origin similar to the glauconite of the Mesozoic and other deposits.

Manganese silicate has been worked in the Loudervielle and Genu districts of the Pyrenees. It occurs interstratified with beds of Devonian age, and on more than one horizon. Locally it has been converted into carbonate and oxide by the action of carbonated and oxygenated waters.

CHAPTER VII

METAMORPHIC ORE DEPOSITS

A LARGE class of deposits, including the ores of a number of the metals, occurs associated with rocks which we know have changed their mineralogical character, and in a measure their chemical composition, since the time of their deposition or original formation. While many original ore-masses have been changed in character, similar metamorphic processes have often given rise to new metalliferous deposits. It is with the changes produced by metamorphism in pre-existing mineral veins and beds that we are here chiefly concerned, for the introduction of new material into the country-rock is treated in the chapters on Pneumatolysis, Hydatogenesis and Metasomasis.

The changes which have affected pre-existing mineral deposits may be divided into two more or less distinct classes : first, those which have taken place in the upper parts of lodes and in the parts of bedded masses of ore exposed to the action of meteoric waters ; and, secondly, those brought about by thermal and dynamic agencies at a considerable depth below the surface.

The changes of the first class are those which have often produced secondary enrichment in metalliferous deposits, and involve the transfer of material from one part of the ore body to another ; also the addition or

subtraction of some ingredient, such as silica, carbon dioxide, or water, producing a considerable change in the composition of the rock as a whole. Such deposits as these are not regarded as truly metamorphic in character, and will be dealt with in the chapter on Secondary Changes; we shall therefore restrict the term 'metamorphism' to express those processes by which the changes of the second class are brought about, and shall include under that heading those reconstructions produced in a rock-mass by the influence of a high temperature, or by shearing stresses of sufficient intensity to generate heat.

The general effect of raising a rock-mass to a considerable temperature above the normal is to bring about a decomposition and destruction of several of its component minerals, and to produce new compounds by a process of exchange between the various acids and bases present in the rock; and it is therefore obvious that such changes can take place without producing any marked alteration in the bulk-analysis of the rock-mass, except, perhaps, the partial loss of water or some other volatile constituent.

It follows that the new minerals formed during the process of metamorphism will be almost entirely dependent on the original chemical composition of the rock and the temperature to which it is raised.

From a study of the metamorphic minerals present in any rock, it is possible to form a very accurate conclusion as to the nature of the rock before metamorphism; whether, for instance, it was an almost pure limestone, a sandy limestone, a shale, or a sandstone, for in each of these cases the new minerals produced by the rise in temperature will have a distinctive character. At the

same time, many of these new minerals give us an indication of the relative temperature to which rock-masses have been raised.

The heating necessary to produce the rise in temperature in a rock, and to bring about metamorphic effects, may arise in two ways—either by the intrusion of a fluid igneous magma into the cooler regions of the earth's crust, causing what is known as an 'aureole of contact metamorphism'; or it may arise from the internal heat of the earth, and affect large masses of rock which are buried at a great depth below the surface, producing metamorphism of the regional type.

Thermal metamorphism is hardly ever a superficial phenomenon, but in the course of ages rocks which have been altered in this manner have been laid bare at the surface owing to the upheaval and denudation of the superincumbent strata.

To give an instance of the process of thermal metamorphism, let us consider the action of heat on a buried mass of impure limestone containing calcium and magnesium carbonates, free silica in the form of quartz, and alumina. At a higher temperature and under pressure, calcium and magnesium carbonate in the presence of silica will give rise to calcium and magnesium silicates such as forsterite, calcium aluminum silicates such as garnet, idocrase, and diopside, and aluminum silicates such as cyanite, andalusite, and cordierite, according to the proportion of each original constituent, and according to the temperature to which the rock-mass is raised.

Besides the formation of entirely new minerals, metamorphic action shows itself in the dehydration of many hydrous compounds and hydroxides of the

metals, and by the simple recrystallization of already existing stable minerals.

The limit of the migration of material during the process of metamorphism is exceedingly small, and therefore the interchange and combination of acids and bases in the original rock takes place only at very close range.

A rock such as a fairly pure limestone undergoing metamorphism will simply recrystallize after all its siliceous and aluminous impurities have acted on an equivalent quantity of limestone, with the formation of calcium aluminium silicates. The presence of forsterite indicates that the original rock contained magnesia, probably in the form of dolomite. Garnet, idocrase, and diopside, in all cases indicate a somewhat impure limestone as the parent-rock; while such minerals as andalusite, cyanite, and cordierite, point with equal certainty to argillaceous sediments.

The ore deposits which existed in areas of sedimentary rocks previous to their metamorphism have, under the influence of heat, suffered distinct changes; for instance, the limonites and the hydrated iron ores, as a class, have been converted into magnetite by loss of water and recrystallization. Pyrites may remain unchanged or be recrystallized, but, if originally mixed with other sulphides, it may combine with them to form the complex compound fahlore.

The impure ores, such as the earthy oxides of iron and manganese, which contain a large quantity of silica, may under certain conditions give rise to the silicates of these metals.

It has been stated that the metamorphic minerals present in any rock are a perfect indication of the

nature of the rock before its metamorphosis, and it follows that a study of the minerals which occur in the rocks enclosing ore bodies will often throw much light on the origin of the metalliferous deposit. For instance, if an ore body of magnetite occurs in an irregular manner in a rock containing garnet, diopside, and similar minerals, it is most probable that the metalliferous deposit was originally a metasomatic replacement of a limestone, and was deposited as the carbonate of iron. If, on the other hand, the deposit be interstratified with beds containing cyanite, andalusite, etc., it is equally probable that the ore was originally an interbedded precipitation occurring in argillaceous sediments.

The crystalline schists, which in some districts are exceedingly rich in metalliferous deposits, are rocks containing a great variety of minerals of metamorphic origin. Most often they have a parallel structure simulating bedding, and marked by alternating sets of distinct minerals. These layers of varying mineralogical character may either result from an original difference in the chemical composition of the successive laminæ of the original rock, or they may be superinduced by shearing stresses.

The metalliferous ores occurring in the crystalline metamorphic rocks form a very large class, and include some of the most important deposits in the world. It appears that under the process of recrystallization, which many pre-existing ore-masses have undergone, the minerals have the power of rejecting their included impurities, and it thus happens that the ores of the metamorphic rocks are often of a particularly high grade.

The ores associated with metamorphic rocks may be

divided, according to their mode of occurrence, into two subclasses : first, those of the crystalline schists in which they occur as layers and lenticles, and which include many important deposits—hæmatite, magnetite, and metallic sulphides. The second subclass includes those larger irregular ore-masses which probably occur as metamorphosed metasomatic deposits, and also many of the so-called metasomatic contact-deposits and veins in which the country-rock contains characteristic metamorphic minerals.

THE ORE DEPOSITS OF THE CRYSTALLINE SCHISTS.

The ore deposits in the crystalline schists, as we now see them, are probably the result of metamorphic action of a regional type on original sediments containing bands of metalliferous material deposited either by direct precipitation or by metasomatic replacement. Their sedimentary origin is supported by their appearance of stratification, and by the fact that a metalliferous deposit is often confined to one horizon over a large area.

DEPOSITS OF OXIDES (HÆMATITE AND MAGNETITE).

These two minerals among the iron ores, especially the latter, are of most frequent occurrence in metamorphic rocks, hæmatite being produced by the dehydration of limonite ; and magnetite by the alteration of ferrous carbonate by loss of carbon dioxide, or by the partial reduction of hæmatite.

The derivation of magnetite from ferrous carbonate is in most cases to be inferred from the mineralogical character of the rock which encloses it.

The country-rock of magnetite deposits has almost invariably been calcareous, and the metamorphic minerals which it contains are most often, therefore, the calc-silicates. Hæmatite, on the other hand, which has most often had its origin in limonite, occurs in a more siliceous gangue.

Hæmatite and magnetite are often interbanded with the crystalline schists and granular gneisses in sufficient quantity to be of great economic importance, and such deposits occur in almost every district where Archæan rocks are exposed at the surface.

Some of the most important are those of Scandinavia, where the thin masses of hæmatite and magnetite, associated with mica schists and similar rocks, are well known and exploited—as, for instance, those of Arndal and the province of Helgeland, in Norway. The North Ranen deposits in the province of Helgeland occur in ferriferous schists and gneissose rocks, as layers of specular hæmatite and magnetite in varying proportions. They hold an average of 13 per cent. of metallic iron, and, although most often in thin beds, occasionally reach a considerable thickness.

DEPOSITS OF SULPHIDES.

The chief sulphide deposits of the crystalline schists are the so-called 'fahlbands,' so well developed in Scandinavia. Although, perhaps, of no great importance in themselves, they have been the source of the mineral matter which has enriched the lodes crossing the district. These deposits contain a great variety of metallic sulphides, either free as copper pyrites, iron pyrites, zincblende, or galena, or combined, together with some

antimony and arsenic, to form the complex mineral fahlore or tetrahedrite.

One of the best examples of the fahlbands may be drawn from the district of Kongsberg, in Norway, which includes the mining areas of Overberg and Underberg. It is a region situated to the south-west of Christiania, and composed of gneisses, mica schists, and hornblende schists, intruded by massive igneous rocks. The direction of the fahlbands and the foliation of the district is north and south, and the dip is at a steep angle to the east. The mineral deposits occur in zones of impregnation, and the sulphidic material, mostly pyrites, is very finely divided. The Kongsberg district also furnishes a good example of the enriching influence of the fahlbands on fissure veins which traverse the country.

In other parts of Norway and Sweden the fahlbands yield valuable ores of copper, such as those of Röraas and Foldal, and cobalt exists as sulphide in the deposits of Skutterud and Snarum, in Southern Norway. In all cases a variety of sulphides are present, but generally one or two metals are present in quantity, and thus characterize any particular deposit.

THE LARGER ORE BODIES OF METAMORPHIC CHARACTER.

We will now pass on to consider those larger ore bodies, associated with the crystalline metamorphic rocks, which were mostly metasomatic in character prior to their undergoing metamorphic changes of a regional type.

DEPOSITS OF OXIDES: IRON ORES (MAGNETITE AND HÆMATITE).

Scandinavia, and especially Sweden, has always been famous for its iron ores, and, as we have seen, has already furnished us with excellent examples of segregations and precipitations. Examples of metamorphic ores are equally numerous and instructive, and the masses are often of great size and importance. The ore mineral is essentially magnetite, often highly manganiferous, with hæmatite and pyrites in varying proportions. Sulphidic ores, however, occur in a similar manner, and in masses of comparable dimensions.

The magnetite is generally associated with recrystallized calcite and a host of iron-calcium silicates, indicating the original calcareous character of the ore-bearing beds.

Masses of this nature are met with at Persberg, Nordmark, Norberg, Dalkarsberg, and in many other localities, associated with calc-silicates, but where the gangue is most siliceous, such as at Norberg, Persberg, and Striberg, hæmatite occurs in greater quantity.

The Persberg deposits, in the province of Waermland, form masses of irregular shape, up to 50 feet in width, in the midst of ancient crystalline rocks, which include recrystallized limestones, and calc-silicate rocks with pyroxene, garnet, epidote, etc.

The Norberg region is similar to the above, but the ores, although associated with metamorphic limestones, have a more siliceous country-rock, consisting chiefly of calc-silicate hornfels and other calc-silicate rocks.

At Dannemora, near Lake Grufsjon, the ore, which is largely magnetite, occurs as lenticles in metamor-

phosed calcareous rocks.   It builds masses occasionally
reaching 50 yards in length by 200 yards in depth, but
there is a gradual passage from the ore body into the
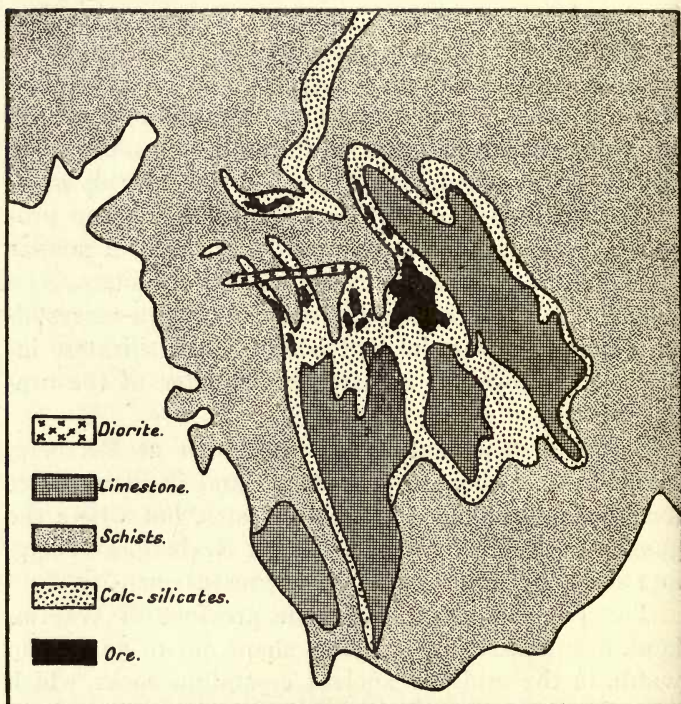
Fig. 61.—Map of the District of Persberg, showing
    the Association of the Ore with Metamorphosed
    Calcareous Rocks. (After Sjorgren.)

Scale, 1 : 11,100.

country-rock.   The metamorphic minerals with which
it is associated include garnets, pyroxene, amphiboles,
etc. ; but perhaps the most remarkable are knebelite, a

manganese-bearing olivine, and dannemorite, an actino-
lite rich in the same metal.

Well-bedded deposits of similar nature to those
described above occur at Örebro, in Sweden, and at
Dunderlandsdal and Naeverhaugen, in Northern Nor-
way. They are associated with mica schists and lime-
stones of metamorphic character. The ore exists as an
iron-bearing mica schist interbedded with limestones
and hornblende schists. Its associates are the usual
calc-silicates, but in addition a garnet exceptionally
rich in manganese.

In other parts of Europe similar ores are found, in
Spain and Portugal with similar associations, and, in
fact, in most regions where the Archæan floor is ex-
posed at the surface.

The Malaga magnetite deposits are due to the meta-
morphism of dolomites which had been partially re-
placed by siderite or hæmatite.

One of the best examples of a metamorphosed
metasomatic deposit is furnished by the magnetite and
hæmatite masses of Mokta el Hadid, in the province of
Constantine, North Africa. Magnetite with hæmatite
occurs in several beds associated with pyroxene-garnet
rocks and mica schists, the calc-silicates representing
in a measure the residual limestone, which had not
been replaced by iron ores.

The deposit as a whole is remarkably free from
impurities in the form of sulphur and phosphorus—a
feature which, in common with a large proportion of
metamorphic iron ores, greatly increases its value. The
iron was most probably deposited in the first instance
as carbonate, which was subsequently converted into
a mixture of magnetite and hæmatite.

In the United States of America, in New Jersey and Connecticut, and in the regions of Lake Champlain and the Adirondacks, magnetite masses occur in the older schists and gneisses, the axes of the ore bodies for the most part lying parallel to the foliation of the districts. The ores have a similar mode of occurrence to those already described, and are associated with an identical set of metamorphic minerals.

The iron ores of Prince of Wales Island, Alaska, occur in masses associated with epidote, garnet, etc., and lie between parallel dykes of olivine dolerite.

Whether the manganiferous iron-bearing series of Brazil, especially that of the Serra do Espinhaço, should be classed with the Lake Superior type of iron ores (p. 257), or whether it should be treated here, is a matter of some doubt ; but on the whole the ores seem to be more closely allied to metamorphic deposits.

In addition to the lateritic iron ores of the central provinces of India, other masses of different origin occur in the Jawadi Hills, in the Madras Presidency. They exist in several bands associated with hornblendic, garnetiferous, and hypersthene-bearing gneisses. They consist almost entirely of magnetite, and are clearly of metamorphic origin. Similar deposits occur in the island of Madagascar.

MANGANESE.

Manganese in the metamorphic rocks usually occurs in the form of hausmannite, braunite, and franklinite.

Hausmannite is similar to magnetite in composition, but the ferrous and ferric oxides of the latter are replaced respectively by similar manganous and manganic compounds. Franklinite may be regarded as a man-

ganiferous magnetite in which part of the ferrous iron is replaced by zinc. Braunite is a compound of manganic oxide and manganous silicate. The manganese ores occur in a similar manner to magnetite, and are usually associated with it, being found for the most part in metamorphosed limestones and dolomites. Such deposits occur at many localities in Scandinavia, as at Nordmark, Långban, Jacobsberg, and in the district of Örebro, at Bukovina in Austria, in Piedmont, and in the Franklin Furnace and Stirling Hill districts of New Jersey, in the United States.

The Swedish deposits of the Örebro district, occurring close to Lake Halftron, are associated with lenticular masses of dolomite included in the granulite-gneisses of that region. The ores are chiefly hausmannite and braunite, and make masses 100 yards in length, by 8 to 10 yards in thickness. Similar to the ore-masses of Örebro are those of Längban, in Waermland, which are also associated with dolomites and granulites. The Jacobsberg and Nordmark deposits occur with magnetite and hæmatite in crystalline limestones.

The zinc-bearing manganese oxides of Franklin Furnace and Stirling Hill, in New Jersey, constitute the mineral franklinite which occurs in the metamorphosed limestones of those regions (Franklin Limestone) in the form of cubic crystals associated with garnet, other calc-silicates, the red oxide of zinc (zincite) and the zinc silicate, willemite. The percentage of manganese estimated as manganous oxide averages about 15.

In Piedmont, in the Val d'Aosta, the ores hausmannite, braunite, and some rhodonite, occur with metamorphosed calcareous deposits and gneisses. They are associated with numerous manganese-bearing calc-

silicates, such as manganese epidote, manganese diop-side, and manganese garnet.

CORUNDUM.

We have seen (p. 57) that this mineral may re-sult from the differentiation of basic igneous magmas, but sedimentary aluminous rocks under considerable pressure, when subjected to the heating influence of the earth's interior or to that of some intruded igneous mass, will undergo a marked reconstruction, often accompanied by the development of corundum. A rock, such as an ordinary argillaceous sediment, in which the contained alumina is not in excess of the silica, will under such conditions give rise to the metamorphic aluminium silicates cyanite, andalusite, cordierite, etc. But should the alumina be more than equivalent to the silica, the excess of alumina will crystallize as corundum. It is to be expected, therefore, that the metamorphosis of a highly aluminious deposit would result in the formation of an almost pure mass of this mineral, and it is interesting to find that the changing of bauxite into corundum has been effected in the laboratory by means of the electric furnace.

Corundum, either in the form of gem-stones, such as ruby and sapphire, or more commonly as emery, occurs in a variety of rocks, but always in those in which there is presumably an excess of alumina over silica.

In metamorphosed impure dolomites and limestones it is met with at Naxos, in Greece, and in the neigh-bourhood of Smyrna. With magnetite and aluminum silicates it occurs as masses in the crystalline schists of many districts. At Ochsenkopf, near Schwarzenberg,

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in Saxony, a mica-talc schist contains it in some quantity, and in the Pyrenees it has been developed largely as a contact mineral at the junction of granitic masses with Palæozoic sediments.

Probably the best-known deposits are those of Northern India, Tibet, and China, as at Mysore, Canton, etc., occurring in thermally metamorphosed aluminous sediments, together with the aluminium silicates cyanite and andalusite.

DEPOSITS OF SULPHIDES.

Masses of iron pyrites, pyrrhotite, and other sulphides, such as copper pyrites, zincblende, and galena, occur in a similar manner to those of magnetite, already described, associated with the same types of metamorphic rocks, including mica-, garnet-, hornblende- and zoisite-hornblende-schists. These sulphidic deposits may be roughly divided into two classes: (a) The copper-bearing pyrrhotites and pyrites, which occur in rocks not particularly rich in silica, and from which there is an absence of limestones; (b) sulphides, including some zincblende and galena, occurring in metamorphosed calcareous deposits.

These sulphide masses are often auriferous, the gold being sometimes original, but most often concentrated by the secondary metasomatic action of the pyrites, etc., on descending auriferous solutions.

It was pointed out, in the case of sulphidic deposits due to precipitation, that they most often occurred in the true argillaceous sediments, and were much less frequently found in association with arenaceous deposits or limestones. Similarly, in the case of the metamorphic masses there is seldom any marked indication

of the original presence of much calcareous material, or, in other words, there is a smaller proportion of the usual calc-silicates, such as were associated with the metamorphic magnetite deposits. The place of epidote, garnet, and diopside, is in such cases taken by more aluminous minerals, such as the micas, chlorites, and the aluminous amphiboles. At the same time, certain masses of pyrites and other sulphides are occasionally found in association with calc-silicates which could only have had their origin in highly calcareous rocks.

It is most probable that the sulphide masses of both the above classes owe their present characters chiefly to a process of recrystallization, together with a certain amount of secondary enrichment and migration of ore material.

The greater number of sulphide masses fall into the first class mentioned above, and include most of those which occur in association with mica schists, hornblende schists, and other metamorphosed aluminous rocks. Examples may be drawn from Ireland, Norway, Hungary, the Carinthian and Styrian Alps, Tasmania, and the United States of America. In Ireland, pyrites masses occur in a series of talcose and hornblendic schists of metamorphic character in County Wicklow.

In Norway, in the neighbourhood of Röraas, which is the centre of an important mining district, deposits of copper-bearing iron pyrites, pyrrhotite, and copper pyrites, are associated with the ancient talc, mica, and chlorite schists, with which they appear interstratified. The masses reach as much as 6 yards in thickness, and extend laterally and vertically for considerable distances. It is supposed that they existed, in the first instance, as precipitations in a sedimentary series, and have since,

together with the sediments, suffered some reconstruction and recrystallization as the result of metamorphic action. There are several other well-known districts in Norway similar to that of Röraas, such as Foldal, to the south-west, where the pyrites masses are equally important, and the island of Karmö, on the west coast. In other countries pyrrhotite and pyrite deposits are met with in Hungary, in the district of Schmöllnitz, associated with metamorphic non-calcareous rocks, with hornblende and chlorite schists in the district of Kallwang, in Upper Styria, and in cordierite schists at Bodenmais, in Bavaria. In extra-European regions we may mention the pyrites masses of Mount Lyell, in Tasmania, and those associated with the hornblende-zoisite schists of the Alleghanies, in the United States.

The Mount Lyell deposits consist essentially of iron pyrites with some copper, and the precious metals gold and silver as accessories. The mining district is situated near the west coast of Tasmania, forty miles south-east of the Mount Bischoff tin deposits. The ore exists as a broad band lying between the chlorite schists and a massive conglomerate ; the pyrites-mass is highly inclined, and has locally undergone considerable secondary enrichment.

The metamorphic origin, as here understood, of the pyritic ore bodies of Mount Lyell has been doubted by Professor Gregory, who in a recent investigation holds that the pyritic masses are metasomatic replacements of the original schistose rocks, and that the lamination of the schists is represented in the arrangement of the pyrites. In this way the deposits are held to be entirely secondary, and the pyrites to have been metasomatically deposited from ascending solutions

traversing faults.   The position of the ore-masses as a whole is entirely dependent on the structural relations of the schists and conglomerates; and it is believed that the various masses were formed in crushed and fractured schists at the points where, during earth movements, they were forced against hard conglomerate masses. The fact that the pyritic masses are traversed by later faults has no significance from the point of view of origin. The same authority has suggested like origins for the pyritic masses of Rio Tinto and Tharsis, and of Rammelsberg and Ducktown.

The sulphide masses occurring with metamorphosed calcareous sediments are characterized by the great variety of the sulphides they contain; in fact, they include all those which occur in the metasomatic deposits.   As examples we may take the ore-masses of many localities in Sweden, of Carinthia, of Lamnitzthal, and of several localities in the Tyrol and Northern Italy.

The Lamnitzthal deposits occur at the junction of hornblende schists with garnetiferous mica-schists; and the ore consists of pyrites with pyrrhotite, copper pyrites, galena, and zincblende.

Those of Panzendorf, in the Tyrol, fifteen miles south of Lienz, are also associated with garnetiferous mica-schists and hornblende schists, and consist of a great variety of sulphides, including all those mentioned above as occurring at Lamnitzthal.   The deposits of Sterzing, also in the Tyrol, occur with hornblende schists and metamorphosed dolomites.

In Northern Italy—at Monte Beth, in the district of Pinerolo, south-west of Turin—sulphidic ores occur in a complex of phyllites, schists, and igneous rocks; they

are associated with calc-phyllites and hornblende schists. There are several other similar occurrences in Piedmont.

The famous Homestake gold ores in the Northern Black Hills of South Dakota occur as lenticular pyritic impregnations in zones in the Algonkian schists, in association with intrusions of rhyolite porphyry. The schists contain contact minerals such as biotite, garnet, termolite, actinolite, titanite, and graphite ; these minerals are consequently found among the ore, which is mainly composed of pyrites, mispickel, quartz, dolomite, calcite, and gold. The pyrites occurs as in-fillings along planes of schistosity, as irregular masses in the schists and porphyry, and in quartz veins. Some parts of the deposit have been shattered by subsequent movement.

METAMORPHIC CONTACT DEPOSITS.

As regards their manner of formation and the con-tained minerals, contact deposits are in most ways similar to those which owe their present characters to meta-morphism of the regional type, but they differ widely in their mode of occurrence. They are found only within the metamorphic aureole surrounding some plutonic intrusion, and result either from the local change in some pre-existing metasomatic or precipitated metal-liferous deposit, or from a metasomatic change pro-duced in the country-rock simultaneously with its metamorphism.

The changes brought about in a pre-existing metal-liferous deposit, as we have already seen, will be of the nature of dehydration or recrystallization ; but the intrusion of a large body of igneous material may result in the introduction of fresh metalliferous material by

means of the heated solutions given off from the magma during the last stages of its consolidation. The formation of ore deposits by such a process bridges the gap between true metasomasis and pneumatolysis.

In our own country there are several good examples of metamorphic contact deposits, the best, perhaps, being the two districts of Haytor in Devonshire and Grampound in Cornwall.

The Haytor mine is situated on the eastern border of Dartmoor ; the ore is in the form of thick beds of magnetite interstratified with altered shales and sandstones of Carboniferous age, and is associated with such metamorphic minerals as actinolite and garnet.

There is little doubt that the ferruginous material was deposited contemporaneously with the shales and sandstones in which it occurs, and in all probability resembled the Cleveland ironstone (p. 245) in many respects. This original deposit was metamorphosed by the great granitic mass of Dartmoor, which breaks across the bedding of the sedimentary rocks, and converted into magnetite. The ores have been altered by surface waters for some distance down the lodes, with the formation of ochre and other secondary products.

The Grampound lode (South Terras, Cornwall) carries magnetite with a little hæmatite, and is associated with calc-silicates, such as green garnet.

In France beds of magnetite and hæmatite occur at several places in the department of Manche, especially at Diellete, in the neighbourhood of Flamanville. The ores are held by Cambrian and Silurian rocks rich in garnet, actinolite, and epidote, the metamorphism being produced by intruded masses of granite. Although such examples are more usually found in connection

with the more acid types of intrusions, such as those of granite, syenite, and the porphyries, basic rocks, such as the lherzolites and ophites of the Pyrenees, have given rise to similar deposits.

The best examples of metamorphic contact-deposits may be drawn from Central Europe, especially from the State of Banat, in Hungary.

The Banat ores consist essentially of hæmatite and magnetite, but are mixed with varying proportions of the sulphides of iron, copper, lead, and zinc. They occupy a belt of country some 170 miles in length, and are confined to masses of metamorphosed Jurassic lime-stones, in which presumably they exist as metasomatic replacements. The metamorphosis was produced by immense masses of syenite and diorite, which were intruded into the older schists. The heat given out by these igneous masses has caused the recrystallization of the limestone, and has given rise to such meta-morphic minerals as garnet, tremolite, actinolite, etc., while the original ferruginous deposit has been converted into a mixture of crystallized hæmatite and magnetite.

In the Moravicza district of Temes (Austria), sul-phidic ores occur in somewhat greater proportion than in Banat.

In Piedmont, in the region of Traversella, magnetite occurs with some sulphides, chiefly chalcopyrite, associ-ated with the metamorphic and igneous rocks of that district. The region is one of ancient gneisses and Palæozoic slates and limestones, which are broken through by numerous igneous masses, including granites, syenites, diorites, and ultrabasic rocks. The most important ores, such as those of Riondello, are met with at the junction of a syenite with other rocks, and

exist in a gangue of calcite, pyroxene, hornblende, and garnet.

Metasomatic iron ores occurring in the Canton de Vicdessos, in the department of Ariege, especially at Rancie, have been metamorphosed into magnetite and hæmatite, and are associated with masses of calc-silicates. Originally the metalliferous deposit existed as a replacement of a Liassic limestone, and was probably similar to the Cleveland ore of England.

Metamorphic magnetite and hæmatite masses are known in a great many more remote districts, such as the Urals and Finland; and with manganese in the neighbourhood of Santiago, in Cuba, in connection with masses of porphyry.

Manganese ores in all cases have a similar origin to those of iron, and therefore it is not surprising to find compounds of this metal associated with the metamorphic iron ores. In Brazil the district of Ouro Preto is noted for its rich manganese and iron deposits. The rocks of this district are schists and gneisses of Archæan age, and a series of schistose quartz-ites, micaceous schists, and limestones, known as the ' Itacolumite Series,' belonging to the Lower Palæozoic division. At some later period than the Lower Palæozoic, intrusions of granitic, dioritic, and gabbroic rocks pene-trated the whole, and produced considerable contact metamorphism.

The Itacolumite Series is the most interesting, as it is the chief ore repository, and contains iron, manganese, and some gold. The micaceous schists pass into pale-coloured calcareous beds, which in turn give place to iron schists and beds of almost pure iron ore, known as ' itabarite.' One of the principal districts is Serra do

Espinhaço, where the ores consist of the metamorphosed residual deposits of limestone, which originally contained carbonate of iron and the carbonate or oxides of manganese.

The manganese ores consist chiefly of the earthy hydrated oxides and pyrolusite, but there is little doubt but that they have undergone considerable changes since their formation.

In the Hautes Pyrénées, the schistose limestones of Serre-d'Arrêt are impregnated with a variety of manganese-bearing minerals of metamorphic origin.

So far we have been dealing almost exclusively with the oxidic contact deposits which are somewhat monotonous in character, but a much greater variety is displayed by the masses of sulphides which occur in a similar manner.

Sulphides of iron, more or less cupriferous, occur, associated with igneous intrusions in metamorphic rocks of many ages and many districts. The most famous deposits are probably those of Rio Tinto, in the province of Huelva in Spain, while similar ores occur at Gavorrano, in Tuscany. The sulphides of iron are themselves of no great value, but as they are usually associated with some copper and other sulphides, and often contain the precious metals, they are frequently raised to great economic importance. All extensive deposits of pyrites should be assayed for gold.

The Rio Tinto deposits occur as masses of iron and copper pyrites, stretching at intervals from Portugal on the west to the borders of Seville on the east. The region is one of intensely folded Palæozoic sediments, intruded by masses of igneous rocks of types varying

from micro-granites to dolerites.   It is with these
igneous intrusions that the pyrites masses are intimately
connected, the ore generally occurring at their junction
with the sedimentary rocks which, as a rule, show con-
siderable signs of metamorphism.

In the Ural Mountains, the district of Bogoslowsk
furnishes a somewhat doubtful example of this class of
ore deposit.   It is said that Devonian limestones have
been contact-altered by intrusive porphyrites, with the
formation of masses of garnet, pyroxene, and idocrase,
and with the introduction of such metalliferous minerals
as copper pyrites.   A similar origin has been suggested
for the ores of Goroblagodat (p. 51) and other locali-
ties, but it does not seem conclusively proved that they
are not segregations from igneous magmas, which have
subsequently been affected by metamorphic action of the
regional type.   A contact metamorphic deposit formed
by the introduction of materials in limestones, at the
moment of their alteration by contact with an igneous
rock, is instanced in the Campiglia Marittima (Tuscany),
where the Temporino vein consists of copper and iron
pyrites, a little galena, zincblende, and mispickel, in a
veinstone of radiating manganiferous pyroxene needles ;
the vein results from the contact-alteration of Liassic
limestone by augite porphyry.

In the United States there are two important districts
containing copper - bearing contact deposits—namely,
those of Clifton Morenci, and Bisbee in Arizona.

The Clifton-Morenci deposits appear to be dependent
on the intrusion of a mass of porphyry which has
produced extensive metamorphism of the surrounding
Palæozoic limestones and shales.   The metamorphism,
which takes the form of the production of new minerals

such as garnet, epidote, etc., is attended by the formation of magnetite, pyrites, copper pyrites, and zinc-blende.

The Bisbee ore masses, in the State of Arizona, must for the most part be classed as true metasomatic

Fig. 62.—Diagram of Micro-Section of Copper and Zinc Ore from the Clifton-Morenci District, Arizona. (Magnified 12 Diameters.) (After W. Lindgren.)

Fc, Fine-grained calcite of normal limestone; C, coarse-grained reconstructed calcite; Q, quartz; S, sericite; G, garnet; Z, zinc-blende; Cu, chalcopyrite.

deposits, for in many cases they occur outside the metamorphic aureoles produced by the post-Carboniferous intrusions. At the same time there are a certain number which occur at the contact of the igneous

rocks with the Palæozoic limestones, and have a gangue of metamorphic calc - silicates.   Professor Lindgren believes that the porphyry magma contained much moisture, holding metallic salts in solution, which was liberated at the time of the consolidation.   Similar deposits may be cited in Vancouver Island.   In Australia, in North Queensland, a good example of a contact copper deposit may be taken from the Chillagoe district, where magnetite, chalcopyrite, and zincblende occur at the contact of igneous and calcareous rocks, in a gangue of garnet, wollastonite, pyroxene, and other calc-silicates.

In Tennessee, cupriferous deposits near Ducktown run parallel to the foliation of mica schists with gneissose bands of Lower Cambrian (Georgia Beds) age.   The ores are mainly pyrrhotite, traversed by strings of copper and iron pyrites with small amounts of sulphides of lead and zinc, in association with calcite, quartz, garnet, epidote, and actinolite.   The pyrrhotite body is a massive infilling, and contains an average of 2 per cent. of copper.

Zinc and lead sulphides occur with the other sulphides in most instances, but the zincblende deposits of Ammeberg, and the galena masses of Sala, in Sweden, are both worthy of special notice.   The zincblende of Ammeberg, to the north-east of Lake Wetter, exists chiefly as lenticles in the Archæan schists and gneisses, but it is also found as a contact deposit in a zone of halleflintas which lies between the younger granitic masses and the schists.

The galena deposits of Sala, north of Stockholm, are associated with metamorphosed calcareous lenticles in the crystalline schists, and are clearly of metasomatic

character, the metasomasis being accompanied by such changes as the marmorization of the limestone, and in a less degree the production of new minerals.

GOLD IN METAMORPHIC ROCKS.

Gold is often found in rocks which have undergone extensive thermal alteration, more especially in conjunction with sulphidic ore deposits of the metamorphic type; but occasionally it occurs in metamorphic rocks independently of any metallic sulphides. It usually owes its presence, in rocks of this nature, either to original sedimentation as detrital gold, or to deposition on pyrites from auriferous solutions by metasomatic action. One of the best instances of gold in metamorphic contact deposits is that of the Deep Creek district of Utah. The *Productus* Limestone, forming a chain of hills, is invaded by numerous veins and masses of granite and porphyry, which have produced powerful metamorphic effects. At the junction of these igneous masses with the limestone we find such metamorphic minerals as garnet and tremolite in abundance, while farther away the limestone has undergone recrystallization. The gold occurs native in two ways: either lying finely divided in the recrystallized limestone in the neighbourhood of sulphidic copper ores, or in fine threads and strings in masses of tremolite.

Gold also occurs in metamorphosed limestones in Nevada; and in the Silver Peak district, solutions, emanating from cooling granitic masses, have deposited the metal in the marginal granite and in the surrounding metamorphic rocks.

In the crystalline schists, gold occurs in small quantities in many districts in America, Europe, and Asia,

and has given rise to some of the richest placer deposits of the world (p. 381).

In the Alleghany region, in the Huronian rocks, pyritous and quartzose lenticles are met with in talc-, and chlorite-schists, the gold being both in the lenticles and finely disseminated through the schists.   Similar occurrences are known in North and South Carolina and the Black Hills of Dakota, in association with talc-, and hornblende-schists; also in Siberia, Northern India, Japan, and the Guianas.

CHAPTER VIII

SECONDARY CHANGES IN ORE DEPOSITS APART FROM METAMORPHISM

THE secondary changes in ore deposits here referred to are those of oxidation, reduction, replacement, transference, or reconstruction of the original minerals, by means of solutions derived either from a depth or from the surface. By far the greater number of these changes are brought about by the action of oxygenated surface-waters, which find their way downwards into the lodes or other ore bodies, dissolving or oxidizing the ores, and causing a redistribution of the minerals, together with a change in their composition. Nearly all sulphidic deposits near the surface show secondary mineral-changes of this nature, the changes being entirely analogous to the ordinary weathering of rocks near the surface. Considerable periods of time must have elapsed in most cases for complete oxidation to be effected, but the porosity of the adjacent rocks, the position of the deposit with respect to the superficial drainage, the ground-water level, and the humidity or dryness of the climate, are important factors which govern not only the extent, but the nature of the alteration. There is always a limit in depth to which secondary changes extend in any particular region, but this gets progressively lower and lower, and keeps pace

with the ordinary process of surface denudation. Where this denudation has proceeded very slowly there is often a large variety of secondary minerals, showing a more or less orderly arrangement as regards their vertical distribution ; the more completely oxidized of the ores are near the surface, but the reconcentrated, more sulphidic types are below, at varying depths, and merge insensibly into the original sulphides. These secondary ore zones are often the richest portions of lodes.

In some regions which have been extensively glaciated, the lodes contain very few secondary ores, owing to the removal by the ice-sheet of the decomposed superficial country-rock, and with it the upper parts of the lodes. The iron and zinc lodes of Scandinavia and of North America may be referred to as examples of this, while in Ontario, according to Volney Lewis, the gossans of the lodes have been removed by the same agency.

Secondary Changes by Ascending Solutions.

The secondary changes of minerals in lodes, effected by waters derived from a depth, are not frequent. They are generally brought about by the solutions of a later period of mineralization, by which the older minerals are largely replaced by newer.

The ores of the Comstock lodes (Nevada) appear to have been largely accompanied by calcite, but this mineral is now met with only in small quantity, owing to its replacement by quartz.

The replacement of barytes and calcite in the cobalt ores of the Erzgebirge, and of the ores of lead and copper in the Black Forest, is connected with a later period of mineralization ; in the latter case, iron and

manganese ores were deposited. To what precise period in the history of some lodes the pseudomorphous replacement of some lode minerals, such as fluorspar, barytes, calcite, quartz, etc., by others, such as iron pyrites, chalybite, limonite, copper pyrites, etc., should be assigned is uncertain; but there is little doubt many of these changes should be ascribed to the ordinary action of secondary concentration by surface waters.

The possibility of the secondary changes in minerals being produced by deep-seated vapours or solutions is suggested by Professor Vogt, who points out that sulphide of silver may be acted upon by hot air or superheated steam, with the formation of capillary native silver and sulphur dioxide, or sulphuretted hydrogen, thus :

$$Ag_2S + O_2 = 2Ag + SO_2;$$
$$Ag_2S + H_2O = 2Ag + H_2S + O.$$
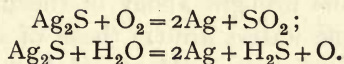
By reaction of the sulphuretted hydrogen with sulphur dioxide, free sulphur or sulphuric acid may be formed, capable of further reactions, which in some cases involved regeneration of the silver glance.

Similar reactions may be effected on other silver ores, or on copper ores, as follows :

$$2Cu_2S + 6O = 2Cu_2O + 2SO_2;$$
$$Cu_2S + 2Cu_2O = 6Cu + SO_2;$$
$$Ag_3AsS_3 + 3H_2O = 3Ag + As + 3H_2S + 3O.$$
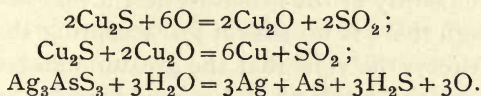
The last of the foregoing reactions is supposed to explain the occurrence of the large amounts of native silver in the Kongsberg district, near Christiania.

In the Kongsberg veins calcite is the dominant

mineral; fluorspar, quartz, anthracite and bitumen, are also present, while barytes is found occasionally. Axinite, soda- and potash-felspar, chlorite, and zeolites, are also met with.   In addition to silver, but in smaller amounts, there are sulphides of iron (in appreciable quantity), zinc, lead, copper and arsenic, and cobalt bloom. The order of mineralization appears to have been—(1) Quartz; (2) sulphide ores and silver glance, with calcite and bituminous material; (3) fluorspar, barytes, with felspars; (4) younger quartz veins, with axinite, iron sulphide, pyrrhotite, and zeolites.   It was in stage 2 that the native silver was formed.

SECONDARY CHANGES BY WEATHERING AND ACTION OF METEORIC WATERS.

The reactions brought about in the upper parts of lodes by surface waters are (1) those of oxidation and (2) those of reduction.   Most sulphidic lodes show that, from their outcrops to a depth of from a few feet to hundreds of feet, the uppermost part consists of a zone of oxidized minerals; while the lower part consists of secondarily deposited minerals, often constituting very rich bodies of ore.   An intermediate zone is often present, which may be regarded as a transition zone, and this is frequently at the ground-water level.

Although there is no reason for accepting the theory in its entirety, the view that the greater number of ore deposits are the result of underground waters has found favour of late years.   It has been held that there are two types of underground water-circulation, known respectively as the ' shallow underground,' or ' vadose,' and the ' deep-seated ' circulation.   It is with the shallow

underground circulation that the changes referred to are connected.

The higher zone of the lodes, also known as the 'belt of weathering,' or so-called 'gossan,' is that in which ores, such as carbonates, chlorides, bromides, silicates, and oxides, occur.

There is frequently a little residual sulphide among the oxidized ores, and nearly all ores of this character are accompanied by greater or less quantities of oxides of iron. In Cornwall the mineral pigotite is sometimes found as stalactites and stalagmites in the working places at depths of 300 feet.

Below this is the ground-water level, or zone of discharge. It is not of great vertical extent, but is characterized by secondary carbonates, oxides, native metals, and by sulphides of copper, lead, zinc, etc., rich in valuable metals, such as gold and silver. Grey copper ore, copper glance, arsenides, antimonides, tungstates, phosphates, and molybdates, also occur here. This zone merges downwards gradually into the static zone, or zone of saturation, in which reducing actions have been dominant, so that there are present secondary sulphides, which in turn pass below into the primary sulphides. The secondary enrichment of copper in the sulphides of the San Domingo Mine, in Southern Spain, admirably illustrates the action. In the sulphide-zones of this mine the percentage of copper present in the ore steadily decreases with depth.

The meteoric waters percolating into the lodes contain small amounts of dissolved oxygen, carbon dioxide, nitrates or nitric acid, and mudeseous or other organic acids, capable of chemically acting on the minerals, which are either oxidized or dissolved and carried down

the lode and redeposited by a second reaction. The dissolved metallic salts, or the free acids occasionally liberated in the general chemical changes, reacting on non-metalliferous minerals in the lode or country-rock, often form secondary non-metalliferous minerals, such as gypsum. The reaction of sulphate of zinc upon limestone may be taken as an illustration.

In dry countries the minerals of the upper parts of the lodes are much more varied than those of moist countries, owing to the more soluble compounds, such as sulphates and some carbonates, being better able to exist in the solid state.

Typical arid regions are those of the deserts of Arizona and of Atacama.

In the upper parts of the cupriferous deposits of Chili, particularly near Copiapo, there is a series of cupriferous and ferric sulphates and carbonates—both neutral and basic—in various stages of hydration, illustrative of the presence of soluble minerals in the gossans of arid regions. Chlorides and oxychlorides are also typical compounds of such districts.

The secondary enrichments of lodes brought about through these secondary reactions are often of great importance commercially. The gold concentration of the Mount Morgan Mine (Queensland), the secondary enrichment of argentiferous ores in the gossan of Broken Hill (New South Wales), the many secondary deposits of copper, lead, and zinc, in the American continent, and those of our own country in Cornwall and other localities, are all examples of concentration of metalliferous lode minerals by secondary processes.

In Guanajuato (Mexico) the secondary alterations (colorados and negros, or pinta azul) extend to depths

of 1,500 feet. From surface to a depth of 250 feet the lodes are poor, but from this level to 1,500 in depth the gold is secondarily concentrated and free-milling. Below this the gold occurs in ores of lead and antimony, and consequently is not so easily separated.

Near the surface the veins sometimes contain black oxide of manganese, and the material here goes by the name of ' que mazon.' At Catorce, where the deposits are in limestone, the colorados extend to a depth of 500 feet, and consist of oxide and sulphate of iron, native silver, chloride, bromide, and sulphide of silver, in a gangue of manganiferous calcite, chrysocolla, cerussite, and azurite.

The secondarily deposited gold is found in ochreous cavities in a quartzose veinstone which once contained pyrites.

When the veinstone was oxidized, the iron pyrites was carried off in the form of ferrous sulphate, leaving the gold, which was originally disseminated through the pyrites, in the form of small segregated masses.

Free gold is found in the gossans of many pyritic lodes, as, for instance, in the Remedios district in Colombia (South America) ; here the lodes contain filiform and grain gold, in an ochreous material extending from the outcrop to a depth of 50 feet, below which there occurs auriferous pyrites, with sulphides of antimony, arsenic, lead, and copper ; the molybdate of lead and native bismuth are also found.

The chemical reactions involved in the changes giving rise to the ores of the gossans, and zones of secondary deposition in lodes, depend on the relative affinities of the metals for the acid radicles, and this may be expressed by writing the metals in a certain order. Thus,

the following series—mercury, silver, copper, bismuth, cadmium, lead, zinc, nickel, cobalt, iron, and manganese —is so arranged that a solution of a salt of any one of these metals will be decomposed by those sulphides of the metals which follow it, but will be unaffected by those which precede it.

One of the commonest metallic compounds of all lodes is iron pyrites, and as this comes at the end of the series with manganese, its effect as a precipitant to salts produced by oxidation of some of the other metallic sulphides must be very great.

In the zone of oxidation (in the gossan) iron pyrites is decomposed by a series of reactions, which culminate in the formation of limonite, a mineral extremely common in the upper parts of lodes.

The oxidation of iron pyrites primarily results in the formation of ferrous sulphate and sulphuretted hydrogen, thus:

$$2FeS_2 + 3O_2 + 2H_2O = 2FeSO_4 + 2H_2S.$$
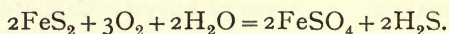
Ferrous sulphate is easily oxidized to ferric sulphate, which in the presence of some non-metallic hydroxide is decomposed, with formation of limonite:

$$Fe_2(SO_4)_3 + 6R.OH = Fe_2O_3 3H_2O + 3R_2SO_4.$$
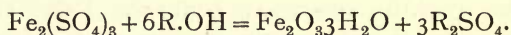
The carbonate of iron is also liable to destruction:

$$4FeCO_3 + 3H_2O + 2O = 2Fe_2O_3 3H_2O + 4CO_2.$$
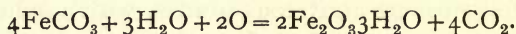
While, if the carbonate contains manganese, an oxide of manganese is formed at the same time.

It has been suggested that the formation of hæmatite from the decomposition of iron pyrites may be effected by alkaline solutions, the action resulting in the formation of alkaline sulphides and thiosulphates. The effect

of the alkaline sulphides and thiosulphates would be to dissolve sulphides of the metals, such as those of copper and silver, which would be transferred to other positions in the lodes. In this series of changes no free atmospheric oxygen is absolutely necessary.

In the manganese deposits of Huelva, in South-West Spain, the psilomelane is a secondary mineral, resulting from oxidation of carbonate of manganese by weathering, thus :

$$2MnCO_3 + O = MnO_2 + MnO + 2CO_2.$$
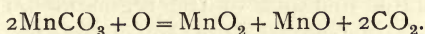
In the presence of pyrites the oxidation is as follows :

$$2FeS_2 + 15O + 4MnCO_3 = Fe_2O_3 + 4MnSO_4 + 4CO_2.$$
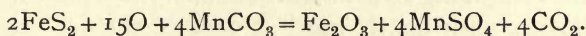
In the reactions involving the sulphates of iron, it is ferric sulphate which plays the more important part, since ferrous sulphate when formed is easily oxidized, and so acts as a reducing agent.

Ferric sulphate is able to act upon chalcopyrite (copper pyrites), with the formation of copper sulphide, which is left as a dark powdery substance. This is next attacked by the ferric sulphate, with the formation of the sulphates of copper and iron, as follows :

$$Cu_2S + 5Fe_2(SO_4)_3 + 4H_2O = 2CuSO_4 + 10FeSO_4 + 4H_2SO_4.$$
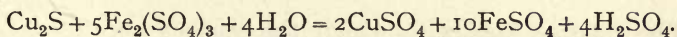
The copper is thus leached out of the gossan in the form of a sulphate, and is carried down the lode into the secondary sulphidic or reduction zone, where, meeting with iron pyrites or other sulphides, it is reduced, with the formation of copper glance :

$$7CuSO_4 + 4FeS_2 + 4H_2O = 7Cu_2S + 4FeSO_4 + 4H_2SO_4 ;$$
$$11CuSO_4 + 5CuFeS_2 + 8H_2O = 8Cu_2S + 5FeSO_4 + 8H_2SO_4.$$
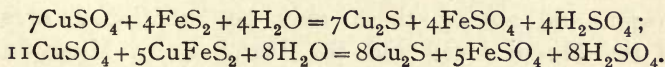
The copper pyrites of the second equation can be regenerated also in accordance with the following reaction :

$$CuSO_4 + 2FeS_2 + O_4 = CuFeS_2 + FeSO_4 + 2SO_2 ;$$
or,
$$CuSO_4 + 2FeS = CuFeS_2 + FeSO_4.$$
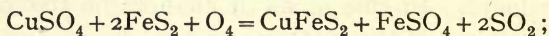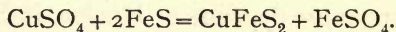
While intermediate compounds, such as bornite, may be formed by similar reactions.

A remarkable instance of the regeneration of copper pyrites is instanced in Vancouver island, where in Bonanza Creek a layer of copper pyrites is found at the surface containing 10 per cent. of copper; this percentage diminishes with depth, until at 20 feet the ore ceases. It is found as a secondary deposit in decomposed surface-rocks, and was probably derived from cupriferous solutions which were reduced by organic compounds.

Native copper is obtained by reduction of sulphate of copper through the action of ferrous salts, which are converted to peroxide of iron or to ferric sulphate.

The reaction corresponds to that represented by the equation

$$CuSO_4 + 2FeSO_4 = Fe_2(SO_4)_3 + Cu.$$
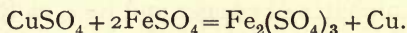
The relative ease with which the various cupriferous sulphides are decomposed by ferric sulphate is indicated by the following order : copper pyrites, bornite, and copper glance.

Although the sulphidic copper-ore deposits invariably show secondary alterations near the surface, there are some exceptionally important deposits of secondary origin, and among these may be mentioned ores of the Mount Lyell and the Burra Burra Mines in

Australia, Rio Tinto ores, those of Chili and Montana (Butte), etc. Deposits of secondary origin are found at Monte Catini, and also in Tennessee.

Sulphate of copper is found in workable quantity in the upper parts of lodes in Nevada, and also in Chili, associated with ores such as the carbonates and silicate of copper.

In the Urals oxidized copper ores, malachite, etc., are common. Impregnations of sandstones by the carbonates of copper occur at Katanga (in Congo Free State). In Poland impure malachite is worked out by the use of sulphuric acid on the country-rock. Auriferous malachite has been found in Guatemala at the contact of syenite with limestone.

The formation of the basic copper carbonate above ground-water level is effected by the action of some soluble carbonate on the copper sulphate in a lode, thus :

$$2CuSO_4 + 2CaCO_3 + H_2O =$$
$$CuO.H_2O.CuCO_3 + 2CaSO_4 + CO_2.$$
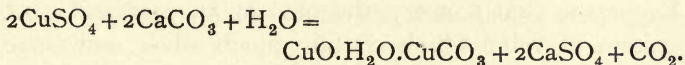
The oxides of copper and the native metal are formed by reactions represented by the following equation :

$$2CuSO_4 + 2CaCO_3 = 2CuO + 2CaSO_4 + 2CO_2.$$
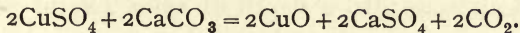
Cuprite (Cu_2O) occurs in quantity in the Cobre Mine (Cuba), and is formed by the reduction of the cupric oxide to cuprous oxide, which by further reaction with ferrous sulphate or free sulphuric acid gives rise to native copper :

$$Cu_2O + H_2SO_4 = Cu + CuSO_4 + H_2O ;$$
$$3Cu_2O + 6FeSO_4 = 6Cu + Fe_2O_3 + 2Fe_2(SO_4)_3 ;$$
$$3Cu_2O + 2FeSO_4 = 4Cu + 2CuSO_4 + Fe_2O_3.$$

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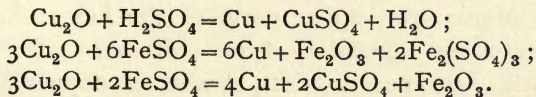
In Chili, near Copiapo, secondary ores of copper, such as copper glance, atacamite, carbonate of copper, cuprite, copper pyrites, and bournonite, are found in fissures traversing Jurassic sandstones and shales, rhyolite, porphyrite, melaphyre, and volcanic tuffs. In the district of Chuquicamata, quantities of atacamite are found in shattered granite, forming a stockwork, to a depth of 300 feet, at an elevation of 7,400 feet above the sea.

Near Antofagasta the ore is mainly atacamite, with sulphate of copper, to 200 feet from the surface. At this level black copper ores are met with, and below these are the primary sulphides.

The gossans of the Western Argentine are auriferous, and even at moderate depths contain carbonates and oxides of copper.

The Peruvian lodes occur in Mesozoic rocks with melaphyres, intruded by diorites and porphyrites. At Recuay in that country, the ores of an east and west system of veins which contain much silver and some accessory copper, and of a north and south series which contains much copper, are largely of secondary origin. At Cerro de Pasco secondary ores are found in veins in altered andesite; to a depth of from 200 to 300 feet the ores are secondary (colorados or pacos); below these come sulphides of iron and copper, which are argentiferous (mulattos or pavanados). The original ores (negrillos) in depth are sulphides of iron, zinc, and copper, with mispickel, tetrahedrite, and bornite, containing silver and gold.

In Mexico the upper parts of the lodes show the characteristic secondary types of ores. In Sonora County (Cananea district), oxides of copper and the

native metal are found in the upper parts of the lodes, while sulphidic ores of lead, zinc, and copper, are met with in depth. In the Moctezuma (or Hedionda) and Chihuahua districts there are notable secondary ore bodies. In the latter district, secondary sulphides, carbonates, and oxides of copper are found as impregnations in beds traversed by veins which contain a little copper ore and much calcite and gypsum.

In Colorado, native silver and copper, oxides of copper, argentite, and other minerals, are found, with compounds of vanadium, uranium, and copper, as impregnations or bedded veins in sandstones.

In the Butte mines, Montana, the oxidized zone extends from surface to a depth of from 200 to 400 feet. In this zone less than 1 per cent. of copper is present, but silver is fairly important. Below this there is a zone of secondarily enriched sulphides, consisting of chalcocite, bornite, copper pyrites, and iron pyrites. With depth these sulphides decrease in quantity.

At Ducktown, in Tennessee, black copper ores of secondary origin are abundant in a narrow zone below the gossan and above the original pyrites. In the gossan large masses of oxide of iron have been worked.

The gossan at the Rio Tinto and Tharsis mines extends in depth to about 150 feet, and consists of oxide of iron. Below this zone a band of secondarily enriched gold and silver ore occurs in a porous earthy gangue. Still deeper are secondarily enriched copper sulphides.

At Broken Hill Mine, New South Wales, the original sulphides are argentiferous galena and zincblende (which

are associated with quartz, felspar, garnet), iron, copper, and arsenical pyrites, lead molybdate, and fluorspar. Secondary incrustations of sooty sulphides are found coating these ores. In the zone affected by secondary changes arsenical and antimonial sulphides of silver, stromeyerite, polybasite, and secondary ores of iron, manganese, lead, and copper, are met with.

In the Virgilina district fragments of bornite are coated by copper pyrites, the whole being cemented by oxide of iron formed through the decomposition of the bornite.

The secondary concentration of zinc and lead ores in limestone by the action of meteoric waters is analogous to that of copper ores, but there appears to be a closer connection between limestone and zinc and lead ores than there is between limestone and the copper ores.

The common lead ore cerussite may be formed indirectly from galena; galena in the upper parts of lead lodes is converted into sulphate of lead, which in turn becomes carbonate through the action of carbonic acid or carbonates in the solutions which ascend the lode. From the carbonate or sulphate the lead may be reconverted to sulphide by the action of sulphides of either iron or zinc :

$$PbCO_3 + FeS_2 + O_2 = PbS + FeCO_3 + SO_2 ;$$
$$PbSO_4 + ZnS = PbS + ZnSO_4.$$
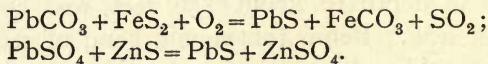
The association of the zinc and lead ores with limestones is explained by true metasomatic action. The sulphides are converted to sulphates, which react on the limestone and replace it by the carbonates of the

metals; while sulphates of lime and magnesia formed during the reaction are carried away in solution:

$$PbSO_4 + CaCO_3 = PbCO_3 + CaSO_4 ;$$
$$ZnSO_4 + CaCO_3 = ZnCO_3 + CaSO_4.$$
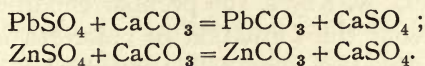
The secondary lead sulphides of Leadville (Colorado), Broken Hill (New South Wales), and the various deposits of lead ores in Nevada, Utah, and many other places in America, are good examples of this type of action. Chloro-carbonates and sulphates of lead occur in Utah, Leadville (Colorado), Tarapaca (Chili), and Sardinia (Monteponi). Phosphate and chloro-arsenate of lead, and basic sulphate of lead and copper, occur less commonly, while the mineral greenockite (CdS) is sometimes liberated on the alteration of zincblende which contains cadmium.

The secondary concentration of the ores of silver is of particular interest, since the richest argentiferous ore bodies have been formed by secondary concentrations; in arid or steppe-like regions, as in the Desert of Atacama, in Northern Chili, the secondary minerals have a special character, owing to the unusual nature of the compounds formed.

The alkaline salts (caliche, Chili saltpetre, or soda nitre) of the Desert of Atacama owe their origin to the nitrification of salts in the old muds and deposits of dried-up lakes, which, owing to the aridity of the region, have not been washed away. Solutions of these salts occasionally find their way into the lodes, and, as they contain chlorides, iodides, bromides, carbonates, and sulphates, a corresponding series of secondary minerals are formed in the lodes. Chloride, bromide, and iodide of silver, with sulphates, carbonate, and

complex ores of silver and other metals, are found together with polybasite and sulphides of silver. According to C. R. Keyes, the peculiar conditions of arid regions favour the formation of chlorides in lodes by reason of the fact that saline substances are carried by winds and deposited in the form of dust.

Sulphide of silver may be regenerated by the action of sulphate of silver on a sulphide. Native silver is formed also by the action of ferrous sulphate on silver sulphate, the reaction resulting in the production of native silver and ferric sulphate, thus :

$$Ag_2SO_4 + 2FeSO_4 = 2Ag + Fe_2(SO_4)_3.$$
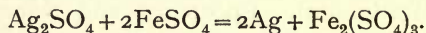
In Sonora County, Mexico, native silver formed in this way is abundant in the upper parts of the lodes.

That native silver is possibly capable of solution by means of $CuSO_4$ or by $Fe_2(SO_4)_3$, with formation of sulphate of silver, and sulphate of iron or copper, respectively, is shown by H. N. Stokes. Under different conditions the reaction becomes a reversible one, and the above equation represents the probable change.

Other secondary minerals found in the upper parts of lodes comprise phosphates (formed by the action of phosphoric acids or solutions of salts derived from the soil penetrating the lodes); arsenides and arsenates; vanadates and chromates (from weathering of gabbros and serpentines) ; molybdates ; ochres of bismuth and antimony ; nickel and cobalt bloom, and occasionally metalliferous compounds of organic acids, such as pigotite (from mudesous acid)—*e.g.*, in Dolcoath Mine.

These secondary minerals occur either as incrustations, as stalactites and stalagmites, or occasionally as impregnations and replacements of the country-rocks near

the lodes. The stalactites and incrustations of calcite and carbonates of copper in limestone caves in Sacramento Hill, Arizona, may be cited. Metallic silicates, such as chrysocolla, are also characteristically found in the upper parts of lodes. In the Platea district, Arizona, carbonate-ores and chrysocolla are met with having a nucleus of copper glance.

CHAPTER IX

DETRITAL AND ALLUVIAL DEPOSITS

THE disintegration of rock-masses by natural agents, such as rain, wind, waves, differences of temperature, and frost, is always taking place in all land areas; it is more or less independent of latitude, but in temperate regions it is perhaps most rapid.

A rock-mass is generally far from homogeneous, and is composed of a mixture of minerals having unequal density, hardness, solubility, and co-efficients of expansion. The greater the physical differences presented by the various constituents of a rock-mass, the more readily will it break down into its component minerals. The material so formed collects at the foot of rock-slopes and on level surfaces of the rock undergoing disintegration, but ultimately, in times of increased rainfall, finds its way into streams, rivers, and finally the sea.

Under the influence of running water particles of solid matter will be sorted according to their size and density.

The transporting power of running water is directly proportional to some power of its velocity, but as a general rule no stream travels throughout its course at a uniform rate. In its more rapid parts it is possibly capable of carrying all the solid material poured into

it by lateral streams, and it can even erode the rocks which form its bed. On the other hand, the widening or bending of a stream, the confluence with a tributary, or the occurrence of bars, banks, large rocks, and other obstacles, will locally reduce the velocity, and incidentally the transporting power. The effect of reducing the velocity will therefore be a deposition of some or all of the suspended solid particles in the order of their respective densities, those with the greater density being deposited first. The greater the difference in density between the various minerals carried in suspension, the more complete will be the separation on deposition.

Sorting may also be accomplished by the simple washing away of the lighter material, thus leaving the heavier particles more or less in their original position ; that is to say, they may remain as a detrital layer on the rock in which they were originally held.

In the case of the metalliferous deposits, the natural concentrations of the heavier detritus are generally termed ' placers.'

The process of concentration as exemplified by the larger rivers may take place in several successive stages, for such streams are constantly eating into and redepositing part of their own alluvium. The alluvia of many of the broader river-valleys are not confined to one level, and occur either as terraces one above the other, marking pauses in the excavation of the valley, or at a considerable depth below the level of the present drainage-system. The former are known as ' shallow placers,' and the latter as ' deep leads.'

The alluvium of any existing river-system is necessarily derived from the areas drained by the main

stream and its tributaries, and its character will be determined by the rock-types present within the basin. It often happens that a river-system receives detrital matter from rocks of many different types, and it is thus quite common to find the alluvium of a tributary differing mineralogically from that of the main stream above the point of confluence. An example is furnished by the River Po and its tributaries, which drain the complex region of Northern Italy. Almost every important tributary of the Po is characterized by at least one easily recognizable mineral which differs from that of the other streams, and is an indication of the rock-types of its particular valley.

It is possible, from an examination of the alluvium of any river, to form, by means of the minerals observed, an accurate idea of the rock-types present within the basin, and also in many cases to track any desired mineral to its source.

All the minerals which are of economic importance in alluvial and detrital deposits have high densities, and are thus easily concentrated by natural agencies. Although running water is undoubtedly the most powerful agent, concentration is also effected by the action of wind and waves.

Wind acts largely on the detritus due to the weathering of rocks in arid climates, and its action is simply that of winnowing, but, together with waves, it also brings about the concentration of heavy minerals from the sands of tidal flats and coastal regions. In the case of short rivers of uniform gradient, there is little decrease in the velocity of the stream until it reaches the sea, where almost at once all the suspended material will be deposited, giving rise to bars and banks.

At low-tides the wind will have power to remove inland much of the fine light material, giving rise to sand-dunes, and at the same time concentration of heavier material will take place on the foreshore. This concentration will be furthered by the action of the waves.
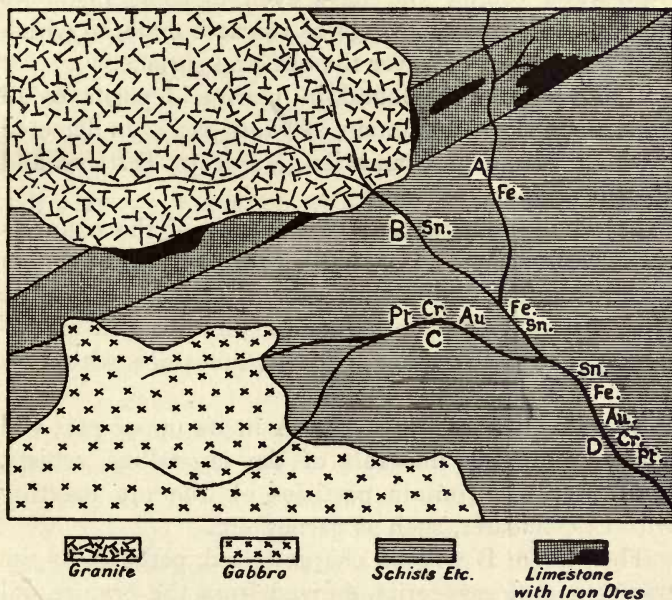
FIG. 63.—MAP TO ILLUSTRATE THE INFLUENCE OF ORE-BEARING ROCKS ON THE ALLUVIA OF STREAMS AND RIVERS.

Detrital deposits containing minerals of economic value are not by any means restricted to recent sediments, for all types of wind-, beach-, and river-deposits occur in the rocks of all ages. The shallow placers are, of course, of comparatively recent date, and are generally dependent on the existing surface conditions;

but the ' deep leads,' although sometimes connected with the present systems of drainage, often belong to so remote a period that there is no traceable relation to the present surface-configuration. They have often been overlain by more recent deposits of marine or fresh-water origin, and have even in some instances been obscured by coverings of volcanic material which has been poured out over the old land-surface.

Beach-placers are found in marine deposits of all ages, and the sorting action of wind has been detected in rocks of the pre-Cambrian, Mesozoic, Tertiary, and Recent periods.

As an illustration of the influence of the country-rock on the character of shallow placers, a river system is shown in the figure, with streams draining a granitic area, a mass of serpentine, and crystalline schists containing lenticles of metamorphic limestone with iron ores.

The alluvium of the stream A in its upper part will contain only the minerals of the crystalline schists, but lower will contain particles of iron ore together with calc-silicates, such as garnet, etc.

The stream B will be characterized, perhaps, by the occurrence of cassiterite, derived from the granite and its metamorphic aureole, associated with such pneumatolytic minerals as axinite, fluorspar, and tourmaline.

The stream C might carry chromite with gold and platinum, and the alluvium of the united streams (D) would contain all the minerals of the tributaries.

We see therefore how, by starting low down a river and going by the character of the alluvium, it is possible to trace any particular mineral to its source, and in this way a great number of rich deposits of

precious metals have been discovered. The placer deposits are always the first to be worked in any district. It often happens that the concentration which has given rise to them is very complete, and then the parent rock may contain the precious material in only the minutest traces.

The number of heavy minerals met with in the placers is extremely large, and includes the native metals gold, platinum, osmium, iridium, copper, silver, nickel, and iron; the sulphides cinnabar, copper and iron pyrites, zincblende and galena; the oxides cassiterite, thorite, chromite, corundum, and zircon; also the spinels, the phosphate monazite, the titanite perovskite, and the silicates axinite, cyanite, andalusite, topaz, garnet, tourmaline, hornblende, and a host of others, all indicative of the rock-type in which they had their origin.

Of these minerals, only a small proportion are of direct economic value, but it has been found that certain non-metallic minerals, of no value in themselves when met with in alluvial deposits, point more or less conclusively to the presence of some ore or metal. For instance, chromite is an invariable associate of platinum; topaz, tourmaline, fluor, and axinite, of cassiterite; and cinnabar, wolfram, and hornblende, might indicate gold.

We will now consider the detrital deposits respectively carrying gold, platinum, tin, copper, iron ores, and the rare earths, such as monazite, thorite, etc.

Detrital and Alluvial Gold.

The disintegration of rocks containing auriferous veins, and the accumulation of gold by the mechanical agents mentioned above, has given rise to deposits

which economically are the most important of all sources of the precious metal. Before proceeding to consider the most prevalent alluvial deposits, we will mention a few of detrital character which have had a slightly different mode of origin.

The chemical weathering of rocks under tropical and subtropical conditions often gives rise to surface deposits of considerable thickness (laterite, etc.). These deposits are due to the chemical changes taking place in the superficial portions of the rock-masses, including the removal of certain constituents by solution, and the oxidation of others. In character they are usually cellular, ferruginous clays which have suffered little redistribution by running waters; should they exist on rocks which are in any degree auriferous, they would contain the metal in greater quantity than the rocks below, and it would be more readily extracted. Such deposits occur, amongst other localities, in the Guianas, Brazil, the Adirondacks, India, Madagascar, and Lydenburg in South Africa. In French and British Guiana and Brazil, the lateritic deposits containing gold are more or less confined to the plateaux and lesser hill-slopes occupied by diorites, diabases, amphibolites, epidiorites, and hornblende schists—rocks which are regarded as the most frequent carriers of primary gold. It has been definitely proved in these districts that the acid gneisses, granites, and porphyries are not the source of the metal.

In the valleys occurs the usual type of alluvial 'placers.' There is little doubt that much of the gold is set free by the complete oxidation of auriferous pyrites, and such an origin has been claimed for the metal in the detrital deposits of the Appalachians.

The Appalachian gold-bearing region is essentially one of mica-schists, but the detrital gold deposits are dependent not so much on the schists, as on a number of basic dykes which cut them.

In India these deposits are more or less restricted to the peninsula, are of Recent or sub-Recent date, and rest on metamorphic and igneous rocks. Most of the detrital gold of India has been derived from quartz veins in the metamorphic rocks, and from chlorite and hornblende schists.

In Madagascar a red lateritic deposit derived from rocks traversed by auriferous quartz veins yields the metal in some quantity, and large nuggets have from time to time been discovered.

The Lydenburg deposits are due to the breaking down and complete oxidation of masses of auriferous pyrites (p. 294), and are connected with a variety of rocks.

The marine and fluviatile detrital gold deposits may be divided into two, according to age—namely, (1) pre-Tertiary, (2) Tertiary and Recent.

In mode of origin the older and younger formations do not differ, but the older are most often marine, and present features, due to mineralization and disturbance, which are consistent with their age. They are generally more compact, the loose sands and shingles having passed into sandstones, quartzites, and massive conglomerates, while earth movements have often caused them to dip at considerable angles with the horizontal.

In almost all cases these gold-bearing beds have been furnished by areas of igneous and metamorphic rocks. The best examples of the older deposits may be taken from the United States, India, Queensland, New Zealand, and South Africa.

In the United States, the region surrounding the Black Hills of Dakota consists of a series of metamorphic rocks, such as hornblende-, chlorite-, and other schists, overlain unconformably by the Potsdam Sandstone (Upper Cambrian). The sandstones and conglomerates of the Potsdam Series are largely made up of detritus from the underlying rocks. They contain gold in a finely divided state derived from the metamorphic series, which is traversed by auriferous quartz reefs. The gold in the sandstones differs from that of
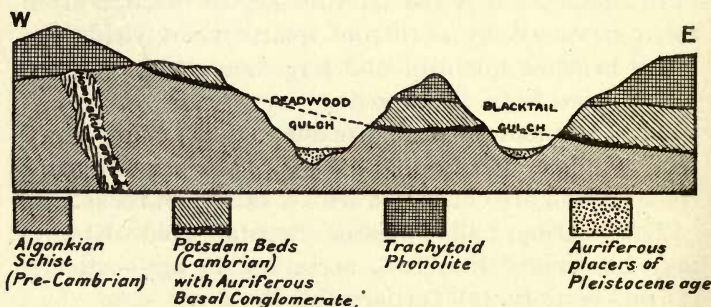
FIG. 64.—SECTION OF THE DISTRICT NEAR LEAD IN THE NORTHERN BLACK HILLS, SOUTH DAKOTA. (AFTER W. B. DEVEREUX.)

the South African bankets in its non-crystalline character and larger grain, but the concentration in both cases has probably been affected by wave action. Similar deposits of supposed Silurian age occur in Queensland, Australia. The Potsdam Sandstone itself gives rise to shallow gold placers of the usual type, in which are found garnet, tourmaline, cassiterite, and other minerals [*e.g.*, at Deadwood Gulch, Blacktail Gulch, etc. (see Fig. 64)].

The chief gold-bearing conglomerates or bankets of

the Rand Goldfield in South Africa occur on several
horizons, in the Witwatersrand System.   The origin of
the gold is still a matter of some uncertainty; by some
it is claimed that it has been introduced subsequently
to the formation of the conglomerates, but the balance
of evidence is in favour of it being in a detrital state
deposited contemporaneously with the enclosing rock.

The Witwatersrand System in its upper auriferous
part is divided into the following series in descending
order :

> The Elsburg Series,
> The Kimberley Series,
> The Bird Series,
> The Main Reef Series,

and has an aggregate thickness of about 10,000 feet.

The gold has been found in each series on one
somewhat variable horizon, marked by conglomerates
separated by quartzite and shales which are not known
to contain the metals.

In the Johannesburg district, the rocks of the Wit-
watersrand System form a synclinal basin which attains
to a length of 100 miles from east to west, and a
breadth of fifty miles.   They are bounded by granitic
and schistose rocks belonging to the fundamental com-
plex, and have been considered to belong to the
Devonian System.   It is quite possible, however, con-
sidering the evidence obtainable, that they are older
than the Devonian, and may even be pre-Cambrian.

They outcrop on the north side of the syncline at
Johannesburg, and on the south at Klerksdorp, Venters-
kroon, Heidelberg, and Nigel.

Some conglomerates also occur at a higher horizon
than the Witwatersrand System, in the Black Reef

Series, at the base of the Transvaal System, and above the Ventersdorp or Witwatersrand amygdaloid (Vaal System).

The banket of the Main Reef Series consists of three or four seams of conglomerate, ranging from 2 to 20 inches in thickness; but occasionally a seam will reach a maximum of about 3 feet.

The gold of these deposits is not visible to the unaided eye, is crystalline, and is, as far as can be judged, only in the matrix of the conglomerates. The pebbles, which are mostly vein-quartz with a little quartzite, do not contain gold except when traversed by cracks; the matrix is highly silicified.

There are several good arguments against the theory of placer-origin for these deposits, and in favour of the introduction of the gold by subsequent infiltration, such, for instance, as the absence of nuggets; but the following facts point more or less conclusively to the detrital character of the metal.

The gold values vary with the texture of the deposit, the coarser conglomerates—those with more matrix in proportion—being the richer.

The gold is restricted to the conglomerates, and is absent from the other sediments associated with them. It was present in the conglomerates before they suffered a certain amount of contemporaneous erosion, with the formation of 'wash-outs.' It is independent of dykes and faults, and also of the distibution of pyrites, which might have acted as a precipitant.

It is assumed, therefore, at any rate for the present, that these deposits were in reality beach-placers—placers similar to those well known in New Zealand and the United States—and that the gold is not the result of

subsequent infiltration. According to Messrs. Leggett and Hatch, the average yield of gold per ton from the Main Reef Series on the Witwatersrand, from 1894 to 1899, was 39·75 shillings.

In America, besides the Potsdam Sandstone mentioned above, auriferous conglomerates of Carboniferous age, which contain the metal in visible quantities, occur in New Brunswick and Nova Scotia.

Detrital gold has been met with in the Permo-Carboniferous rocks of the Gondwana system of India, especially in the Talchir Conglomerate, also in pre-Coal-Measure rocks of New South Wales.

Amongst the supposed Tertiary deposits, we may mention the deep leads of the south-western part of the United States, and of Gipp's Land and Victoria in Australia.

Before leaving the subject of the older detrital auriferous deposits, it must be pointed out that all coarse sediments and conglomerates which have been formed directly from material derived from ancient crystalline rocks may contain the metal, and such deposits should be assayed. There are untried conglomerates in our own islands derived directly from igneous and metamorphic rocks of pre-Cambrian age, which may perhaps prove of value at some future date.

The gold of the shallow placers and deep leads of Tertiary and Recent ages occurs generally as small particles devoid of crystalline form. Occasionally nuggets of great size are met with, and their origin has been a subject of much speculation.

In Australia the placers have afforded nuggets up to 233 pounds in weight, but, in view of the fact that masses weighing 140 pounds have been found in quartz

reefs, it does not seem necessary to claim for the placer nuggets any other than a detrital origin. It is, however, possible that the welding of small particles of gold into nuggets may take place naturally during the formation of alluvial deposits.

The gold of placers is usually associated with some silver, which, when in considerable quantity, gives the alloy an exceedingly pale colour. It is also found, associated with platinum and the allied metals, in some of the gravels of the Sierra Nevada and Brazil, in the deep leads of Victoria in Australia, and in the rivers of Assam and Mysore in India.

The richest alluvial deposits are always adjacent to, if not resting on, the parent-rock, the coarser gold being nearer the source.

In Europe examples of alluvial gold deposits may be drawn from the British Isles, France, Spain, North Italy, and Central Europe.

In England gold occurs in almost all the alluvial tin deposits of Cornwall (p. 399), associated with cassiterite magnetite, wolfram, and less frequently molybdenite, derived from the granites of the county, the metamorphic aureoles, and the veins in the killas.

In Ireland it is met with in the gravels of the Gold Mines River and other streams in County Wicklow, with an assemblage of minerals similar to those of Cornwall.

In Scotland it has been washed from the alluvium of the streams draining the Leadhills, and has had its origin in auriferous pyrites. In Wales it occurs in the alluvium of the Cothi, in Carmarthenshire, and has been derived most probably from the numerous small quartz-veins which traverse the older rocks.

In Central Europe gold has been found in small quantities in the alluvium of the Rhine and several of the larger rivers draining the Alps and Carpathians. The Rhine alluvium has been exploited between Rheinau and Dexland, about fifty miles from Basle where it contains, besides some gold, titaniferous iron ore and traces of platinum. Gold occurs in the rivers of Northern Italy draining the Alps of the Monte Rosa district, and of France and Spain draining the igneous and metamorphic rocks of the Pyrenees.

In Asia the rivers of the Ural Mountains and Siberia have long been famous for their alluvial gold and platinum. In the Ural district, the noted field of Bogoslowsk lies to the north, and includes the minor districts of the Rivers Lozva and Sossva, tributaries of the Tavda. The parent-rocks are chiefly diorites and serpentines.

Farther south lie the chlorite- and talc-schist district of Ekaterinburg, beyond which is the rich field of Zlatoust.

In the latter district the auriferous alluvium occurs along the tributaries of the Miask, which itself flows in the granitic and gneissose district between the Ilmen Mountains and the Urals.

The Miask placers are some of the richest in the Urals, and are famed for the large nuggets which from time to time have been discovered. Thirty miles from Nizhne Tagilsk auriferous gravels lie beneath peat mosses.

In Central Siberia the great district of the Yenisei is one of igneous and metamorphic rocks, while to the west lie the subsidiary drainage areas of the Vitim, the Olekma, tributaries of the Lena, and of the upper part

of the Amur.   The deposits are often covered by peat, varying from 2 feet up to 160 feet in thickness; but as a rule the overburden does not exceed 12 feet.

The auriferous deposits of the Northern Yeniseisk district all contain bismuth, magnetite, and occasionally garnets; but those of the southern area contain brown iron ores, iron and copper pyrites, and occasionally native copper.

Near the head-waters of the Yenisei occur the deposits of the Atchinsk and Minussinsk districts, where the rocks are chiefly granite, diorite, syenite, diabase, and basalt.   In China the province of Shantung has been the main source of Chinese gold for centuries. The ore occurs in river-alluvia, but the bed-rock is difficult of access owing to large amounts of water.

Alluvial gold has been found in India, Turkestan, and Afghanistan, also in a great many districts in Tibet, China, and Burma, and in the islands of Sumatra, Borneo, and Japan.

In India most of the streams of Assam, Mysore, Madras, Bombay, Hyderabad (Haidarabad), Chota Nagpore (or Chutia Nagpur), and Northern India, which drain areas of metamorphic rocks and the Gondwana formation, contain the metal.

The Permo-Carboniferous rocks, as we have seen, contain detrital gold.   It occurs also in the alluvium of the Godaveri, in the neighbourhood of Godalore. The streams of the Himalayas are practically barren.

The deposits of Sumatra occur chiefly on the western coast, in a region of metamorphic schists traversed by granites.   The ore, in place, exists as quartz-veins with copper and iron pyrites, traversing the schists, and in association with diorites.

In Africa the chief detrital gold deposits, in the form of shallow placers, are those of the northern States, such as Tunis, and those of the streams draining the Abyssinian highlands.

In the region around the Gulf of Guinea, deposits exist in the upper part of the Senegal basin, as at Bambuk, Bambara, etc., and on the Gold and Ivory Coasts. The parent-rocks are largely metamorphic in character, with some trachytic lavas. Gold also occurs along the course of the Lombigo, in the kingdom of Angola.

In South Africa many shallow placers exist in the districts of Lydenburg and Eersteling, in rivers of the Northern Transvaal, in Matabeleland south of the Zambesi, and in the district between Lake Nyassa and this river.

In North America there are a great number of districts where auriferous placers have proved a valuable source of the metal. The chief districts are those of Alaska, British Columbia, Nova Scotia, California, Colorado, and Carolina.

In Central America we may mention Honduras, and in South America the Guianas, Venezuela, Ecuador, Brazil, Peru, Bolivia, and Chili.

The Alaskan deposits have a wide distribution, and the gold has been concentrated by streams fed by the glaciers and snowfields. The placers are more or less restricted to a belt of country two or three hundred miles in width, which stretches north-west-ward from the south, Pacific, coast, crosses the Arctic Circle, and bends westwards to the shores of Behring Strait.

The source of the gold has been supposed to lie in the

small quartz-veins and stringers which occur in the metamorphic schistose rocks. This is true in a measure, but there seems reason to believe that gold-values are also controlled by basic igneous dykes, epidiorites, etc., as in the Guianas and many other districts. The gold of the Alaskan deposits has not travelled any great distance, and occurs either free or associated with pyrites. On the coast certain beach-placers are extremely rich.

In British Columbia nearly every stream contains gold in its alluvium, but the richest placers are connected with the Rivers Anderson, Fraser, and Columbia, including between them the district of Cariboo. The working of these deposits, which consist largely of re-sorted glacial drift, is greatly impeded, as in Alaska, by the climate.

The parent-rocks are chiefly talcose and chloritic slates and schists, which occasionally show signs of intense metamorphism.

The Cariboo district, which is probably one of the most important, consists of a dissected plateau with an average elevation of some 5,000 feet above sea-level The deep valleys are lined with an accumulation of glacial drift, often 150 feet in thickness, through which the rivers make their way and carry on the processes of sorting and concentration. In these valleys the auriferous deposits often exist both as shallow and deep placers, the latter lying beneath a 'false bottom' of consolidated and almost impervious drift.

Farther south, in Vancouver Island, similar rocks have given rise to fairly rich placers, especially in the Leech River district.

In Western Canada valuable placers occur in connec-

tion with the Whale River, and with the Chaudière River in Quebec.

In the northern States of the United States, such as Oregon, Washington, Montana, Wyoming, and Dakota, auriferous alluvia are well known.

In Central Washington the placers are similar to those of Alaska in character, but the gold is of a very pale colour, owing to the fact that it is alloyed with a certain amount of silver.

The Wyoming deposits are of interest in so far as they contain platinum, and the Dakota shallow placers have already been mentioned in connection with the Potsdam Sandstone.

In Montana and Idaho placers have been met with in the Elk City district at American Hill and Tiernan, those of the latter place being between 4,000 and 5,000 feet above sea-level. They vary in thickness from 60 to 100 feet, but the gold is almost all contained in the lowest 20 feet. The bed-rock consists of gneisses intruded by veins of pegmatite.

In the western States, the alluvial deposits of California, Nevada, and Colorado with New Mexico, are some of the most famous in the world.

The Californian placers occur on three distinct levels, and belong to three different ages. The oldest occupy the plateaux, and rest directly on the parent-rock; they are not connected in any way with the present drainage system, and are considered to be of Tertiary age. Of more recent date are the gravels of the present valleys, which exist in at least two stages. The older valley gravels form terraces flanking the hill-sides; they have been cut through at later periods by the river, which has deepened its valley and left the older gravels high above

the present drainage-level. Occasionally they have been covered by flows of lava, as in Tuolumne County, and are in many instances worked as deep leads beneath a roof of volcanic rock. The youngest deposits consist of the alluvium of the rivers, as now forming in the river-bed and on the flood-plains.

The chief districts where such placers are developed are those containing the three Yubas and their tributaries, while plateau-deposits occur between the valleys.

The source of the gold is in part in the metamorphic and igneous rocks of the ancient complex, but the distribution of the metal seems to be governed to some extent by quartz veins which traverse the Jurassic rocks of the Sierra Nevada, and also by diabase intrusions and lava-flows.

The gold in the veins of the Cripple Creek and Black Hills districts exists in depth partly as telluride, but at the surface it is most often native. In fact, in such districts as Nevada, the San Juan region of Colorado, Cripple Creek, and Mexico, the placers are derived from propylitic gold-veins connected with altered andesites, from the fluorspar-bearing telluride veins, and from sericitic and calcitic masses which also yield a variety of metallic sulphides.

Iridium has been found in the placers of the Sierra Nevada.

In Central America and the West Indies alluvial gold occurs in Honduras and Hayti. In Honduras the placers are most common on the Atlantic slope, and have had their origin in sulphidic quartz reefs which contain auriferous pyrites, galena, zincblende, cinnabar, and stibnite.

In Hayti they are derived from quartz veins traversing the metamorphic talcose slates which are in contact with syenites and other crystalline rocks. They are best developed in the basins of the Nigua and Jaina Rivers.

In South America placers occur in Ecuador, Bolivia, Peru, the Guianas, Venezuela, Brazil, Chili, and the Argentine.

In Ecuador they are found in the valleys of the headwaters of the Amazon; in Venezuela and the Guianas, in the valleys of the Aroa, Yuruari, and Saramacca, where the gold-values are controlled by the presence

FIG. 65.—SECTION TO ILLUSTRATE THE MODE OF OCCURRENCE OF DETRITAL METALLIFEROUS DEPOSITS (PLACERS, ETC.).

of diabase, diorite, hornblende schists, and allied rocks, and are independent of the more acid gneisses and intrusive rocks which occupy considerable areas. The parts of the basic rocks which are richest in iron ores, especially pyrites, are also richest in gold.

In Brazil auriferous placers have been worked in the districts of Bahia, Minas Geraes, and others, but chiefly in the neighbourhood of Preto, and on the borders of Uruguay. They contain a great variety of heavy minerals, especially certain compounds of the rare earths. Stibnite has also been detected in some instances, as well as native iron. At Tripuhy, the

antimonial titanates of iron and calcium (derbylite and lewisite), together with tripuhyite (Fe_2O_3,Sb_2O_4), are found in gravels containing cinnabar.

In Chili, where the rivers are almost all short and rapid, the placers are confined to the coastal regions, and are derived entirely from the volcanic and metamorphic rocks of the Andes.

Australia has long been noted for the production of large quantities of gold, and, as in most other cases, the earlier mining was more or less confined to the shallow placers. Detrital gold deposits occur chiefly in Victoria, New South Wales, and Queensland ; in character and age they correspond closely to the placers of California, for they occur as plateau-deposits, deep leads occasionally covered by lava-flows, and as shallow placers. The recent alluvium is often formed at the expense of the more ancient detritus.

In Victoria deep leads are well developed in the Murray River district, while similar deposits are overlain by basalts, regarded as of Pliocene age, in the Eastern Plateau and Gipp's Land.

In the Ballarat district detrital deposits of several ages are met with, and in Gipp's Land they are well developed in the Valley of the Dargo, and are derived chiefly from Lower Palæozoic rocks. Victorian placers, besides the usual minerals, are known to contain topaz, pleonaste, sapphire, wolfram, and cassiterite (p. 403), especially in the districts of Maryborough and Castlemaine. They have been derived from a variety of rocks, amongst which hornblendic rocks and granites play a prominent part.

In New South Wales the capital lies in the centre of the auriferous tract, but the placers of the interior are

difficult to work on account of the shortage of water. Gold occurs in the sands of the River Clarence in association with cinnabar. The most valuable detrital deposits are the marine placers, such as those of Montreal, and Corunna, fourteen miles to the north, which are black ferruginous sands, derived from basic igneous rocks, and contain a good percentage of gold. Similar deposits occur at Wagonga, and below the silt of Wallaga Lake.

The alluvia of the rivers of Queensland, on the seaward side of the coast range, all yield gold in small quantities; but on the other side, flats and narrow strips of alluvium are fairly rich. The gold has been set free by the oxidation of auriferous pyrites in the country-rock. Some of it is alloyed with silver; it has also been found on the high-level plateaux.

In South Australia the River Torrens yields the metal in small quantities, but fairly rich placers occur in the districts of Echunga, Jupiter Creek, and Barossa thirty-five miles from Adelaide.

The Echunga and Barossa deposits are shallow placers and deep leads, derived most probably from auriferous quartz-reefs. The deep leads in Victoria are considered to be of Pliocene age, and vary from 20 to 100 feet in thickness.

In Tasmania placers occur at Lisle, near Mount Arthur, and along the Pieman River, near the west coast.

In New Zealand the auriferous deposits are chiefly confined to the southern island, along the western coast, west and south of the Great Divide. They are best developed in the districts of Otago, Westland, and Nelson, representing an area of some 20,000 square

miles. They consist of the ordinary shallow placers, of a thick series of gravels of Tertiary age in the wider valleys, and recent beach-placers. The Tertiary gravels, as developed in the Otago and Charlestown districts, are partly concreted, yield varying quantities of gold, and rest usually on a denuded surface of the parent-rock.

Stanniferous Detrital Deposits.

Nearly all the important tin-fields of the world contain, in addition to lodes, deposits of detrital tin-ore derived from the wearing away of the granite and contact-metamorphic rocks in which the tin-lodes occur. The cassiterite is as indestructible as most other minerals of which alluvial deposits may be formed, and, although often found in grains of microscopic size, is nevertheless capable of being concentrated into workable deposits by reason of its high specific gravity.

In its concentration in true alluvia, the lighter argillaceous, micaceous, or very fine sandy material, derived from the degradation of the rocks during the liberation of the ore from the lodes, is washed away from the heavier particles of tin ore which settle in layers in the lower parts of the deposits, and which may be subsequently covered by sands or gravels containing no tin ore. This more particularly happens near the mouths of stream-valleys which have been submerged.

As a shoad-material it is also found on gentle slopes below the outcrops of tin lodes, mixed with ordinary superficial broken and decomposed rock, or 'head,' a formation which, although travelling gradually down the hill-slopes with more or less rapidity according to the

climatic conditions, cannot be regarded as a true alluvial deposit.

Occasionally, as at La Paz, in Bolivia, the tinstone is found among heaps of coarse débris and boulders in mountain torrents.

Its occurrence in sea-beaches is exemplified in Cornwall, where small primitive dressing plants are occasionally seen treating the beach-sands in coves such as those at St. Just and other places.

In the older upland flats or peat-mosses of Cornwall tin ore occurs at the base of the detritus, and also in the streams draining the flats.

Of the older buried Tertiary alluvial deposits, it is principally those which have been protected by lava-flows, as in New South Wales, that have survived the general weathering and denuding agencies ; these remain as workable deposits below the igneous rocks.

In the stanniferous layers of the detrital deposits, characteristic minerals derived from the more inde-structible portions of the rocks in which tin lodes occur are also found — quartz, topaz, tourmaline, axinite, garnet, epidote, wolfram, scheelite, fluorspar, monazite, ilmenite, magnetite, etc. Gold is occasionally met with, and also precious stones.

In Perak some decomposed stanniferous pegmatites have been mistaken for alluvium.

TYPICAL EXAMPLES OF STANNIFEROUS DETRITAL DEPOSITS.

Cornwall.—Cornwall may be taken as furnishing excellent examples of the different modes of occurrence of detrital tin ore. The principal deposits, although for the most part turned over and worked out, are met

with in the inland detrital flats, or so-called 'moors.
These moors or mosses are wide, irregular, shallow
hollows, often united by low divides, infilled with coarse
detrital material and tinstone, and overlain by layers
of sand, gravel, and peat, of no great thickness. The
principal of these moors, the Goss Moor and the Red
Moor, etc., near St. Austell, are situated at a level of
about 400 feet above the sea, on what appears to be the
relics of an old marine shelf or platform, cleaned and
sharpened up in Pliocene times. At various levels,
either above, up to, or below 700 feet, less conspicuous
detrital flats occur, which have also, in times past,
been worked for tin ore, and more recently for wolfram.

These moors extend laterally in tributary-like arms
up to altitudes of 700, 800, or even 1,000 feet, and the
detrital material in them appears to merge insensibly
into 'head,' the pre-Glacial decomposed fragmental
rock which covers as a mantle the whole of the West
of England. The flats, the widest of which is the Goss
Moor (one and a quarter miles), have a comparatively
rapid slope towards the streams which drain them, the
gradient being that of torrential conditions, varying
from, but rarely exceeding, an angle of thirty minutes.
The tin-ground is mainly confined to channels at the
base of the detritus, and rarely exceeds a few feet in thick-
ness. The material consists of coarse or fine subangular
fragments of schorl-rock, greisen, granite, hornfels, and
other igneous and metamorphic rocks, with quartz.

The streams which drain these upland flats or
mosses are in comparatively narrow V-shaped valleys,
the mouths of which have been silted up at the coast,
owing to submergence of the land since their erosion.
In the lower reaches, therefore, the tin deposits of the

streams are below the level of the sea, and buried beneath great thicknesses of beds of sand (both river and sea), gravel, silt, peat, and submerged forest, up to 90 feet. Such streams have had their alluvium turned over for stream-tin from the coast to their source.

The beach-sands of some of the coves round the Cornish coast are worked in a small way occasionally. The tin ore extracted from them occurs partly as a natural constituent of the sands, or is partly derived from the waste material flowing down the streams from the dressing floors of the inland mines.

The tinstone which occurs in the 'head' is of the nature of shoad-material. The 'head' is a relic of ancient weathering under special climatic, probably partly steppe-like, conditions. As the district was never glaciated, the superficial fragmental rock has been allowed to accumulate, and under special conditions has crept or been washed down the slopes into hollows, from whence much of it has found its way into the moors.

The working of stream tin in Cornwall is very ancient, and has been mentioned by old classic writers, who give accounts of the early tin-trade between Cornwall and the Mediterranean ports.

An idea of the enormous yield of tin ore from the alluvial deposits (which contained, generally, considerably under 1 per cent. even in the richer patches) may be obtained from the estimate by Mr. J. H. Collins, who states that between 1201 and 1800 A.D. 550,000 tons of metallic tin were yielded by the stream-tin-works alone.

The Malay Peninsula; Banka and Billiton.—The detrital tin deposits of Malay are the world's most

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important supply of this metal. The principal deposits are contained in the States of Selangor, Perak, and Pahang. The line of granite intrusions, forming the higher lands of the Malay Peninsula, extend from Siam to the islands of Banka and Billiton, and throughout are associated with tin ore.

The deposits consist of the usual admixture of materials derived from granite, and Palæozoic shales, limestones, and quartzites. The minerals found in them, in addition to quartz, comprise magnetite, ilmenite, tourmaline, topaz, hornblende, monazite, sapphire, wolfram, and scheelite.

As in Cornwall, the deposits consist of layers or beds of various materials, and reach a thickness of 100 feet or more, but the tin-ground itself may average from 4 to 15 feet. The Kinta Valley, which is the most important of the alluvial tin-producers, is a wide drainage area, measuring about forty miles in length, thirty miles in width at its southern end, and five miles at the northern end. The material wrought contains from $\frac{1}{2}$ to 1 per cent. of metallic tin, but in places as much as 20 per cent. The so-called ' karang ' is the tin-ground proper, and often occurs stained or firmly cemented by limonite, produced by the oxidation of carbonate of iron solutions percolating through the bed.

The so-called ' kong ' is a type of detritus consisting of a stanniferous mixture of very fine-grained and coarse material. According to Mr. Scrivenor, the State geologist, the term ' kong ' is used loosely for material having two modes of origin. In one case it is merely kaolinized or rotted pegmatite, consisting of a mixture of kaolin and quartz, mistaken for detritus;

but in the other it is a true detritus, in the form of impalpable powder, consists of fragments of quartz and other materials, and contains no kaolin.

An exceptional form of detrital deposit, in Perak, has lately been described by Mr. Scrivenor. This is the so-called 'Lahat Pipe,' an irregular pipe-like body of tin-ore, extending to a depth of over 300 feet in the limestone of the Kinta Valley. This pipe was originally a stanniferous vein, but subsequently became a course for surface water; much of the limestone was dissolved away, and a solution cavity was formed into which the tin-stone fell and became cemented into a brecciated mass. Hence the ore is a residuum *in situ*.

In Banka and Billiton the stanniferous detritus occurs in two ways. In the first the tin ore is found as shoad-material on the hill-slopes or plains, not far from the lodes from which it is derived; but in the second it is met with in the ordinary valley-deposits, which range up to about 50 feet in thickness.

The true tin-ground rarely exceeds 3 feet, and is usually covered by sands and clays which seldom exceed 30 feet in thickness.

The minerals found in the tin-ground are quartz, topaz, monazite, iron ores, manganese ores, bauxite, wolfram, and gold, with fragments of the country rock, and clay.

The Stanniferous Alluvia of Australia and Tasmania.—The deposits occur in both Recent and in old Tertiary river-valleys protected by basalt flows from the denudation which would have destroyed them. The protected deposits are known as 'deep leads.'

The deposits of New South Wales occur in the New England district, the more important alluvia being

those of Vegetable Creek, Stanthorpe, Cope's Creek (near Inverell), and Watson's Creek.

In the deep leads of Vegetable Creek the Tertiary valleys have been filled in by successive flows of basalts, and the total thickness of material overlying the tin-gravels may in places amount to over 500 feet. Zircon, garnet, topaz, tourmaline, gold, and wolfram, are associated with the cassiterite.

Of the Tasmanian deposits, those near Mount Bis-choff are of the most importance. The tinstone occurs in the decomposed fragmental rock which covers the slopes of the hills, and is a true shoad - material, somewhat similar to the Cornish 'head.' In part the deposit is like scree ; it extends to the tops of the hills, and ranges in places up to 70 feet in thickness.

The hills themselves are composed of Palæozoic argillaceous sediments and limestones, cut by quartz porphyry dykes, all of which are traversed by tin veins. To the residual deposits the term 'face' is locally applied. The so-called 'white face' lies near quartz-porphyry dykes, and consists of pieces of stan-niferous quartz-porphyry, with finer fragmental material and sands containing tin ore and other minerals.

The 'brown face' is situated in basins near quartz porphyry dykes, and consists of fragments of highly altered stanniferous quartz - porphyry and slate ; it reaches nearly 300 feet in thickness, and is cemented by limonite and other ferruginous oxides.

The Stanniferous Alluvia of Saxony and Bohemia. —As in the stanniferous 'head' of Cornwall, tin ore is found in fragmental material covering the hill-slopes in the tin-bearing regions of the Erzgebirge, as at Geyer and Eibenstock. The most important deposits

of this region are, however, those of the river-valleys, which can be broadly grouped according to their age as Recent or Tertiary.

The modern valleys which drain the stanniferous areas, like those of Cornwall, are filled with alternating layers of gravels, sands, clays, and peat. The coarser detritus at the bottom of the valleys consists of rounded fragments of granite, contact-altered killas, and pieces of veinstone. In addition to tin ore, beryl, apatite, topaz, fluorspar, and carbonate of iron, with some gold, are found as minerals which are paragenetically related.

The Tertiary alluvial deposits are only represented in one place in the Erzgebirge, and that is near Abertham (at Seifen). Here there is an old river-bed of early Oligocene age, filled with stanniferous gravels alternating with tourmaline- and quartz-sands and clays, which are covered by flows of basalt and phonolite.

The deposits are analogous to those of New South Wales, and have yielded large amounts of tin ore.

Miscellaneous Alluvial Tin Ores.—At La Paz, in Bolivia, a coarse detritus, consisting of boulders and other débris, is found in mountain torrents, and worked for the detrital tin ore which it contains.

In the alluvia of the Embabaan district in Swaziland, South Africa, tinstone is met with in association with monazite, corundum, magnetite, and other substances, of which some are derived from stanniferous pegmatites.

PLATINUM AND ALLIED METALS.

The description of the detrital gold deposits given above applies also to those placers which contain platinum, except that platinum-placers are almost

always derived from one type of rock, while gold may be furnished by a greater variety.

It was seen in an earlier chapter (p. 34) that the original source of almost all platinum, and the allied metals osmium and iridium, lay in ultrabasic and basic igneous rocks. It is therefore not surprising to find that all the platinum-placers are due to the breaking down of rocks of this character.

In Europe and Asia, platinum, associated with osmium, iridium, gold, and the mineral chromite, occurs in the placers of the Ural Mountains, in the districts of Nizhne Tagilsk, Goroblagodat, etc. The placers of the Nizhne district are derived from the peridotite masses of Solovsaia.

Although the Ural placers taken as a group are the richest in the world, platinum has been discovered in many other regions, such as in the auriferous gravels of the Miask district, in the alluvium of certain rivers in Borneo derived from serpentines and gabbros, and in the rivers of Assam.

In New Zealand the placers of the River Tayaka are very similar to those of the Urals; they contain osmium and iridium as well as platinum, and are derived directly from peridotites.

At the Ruwe gold mine, in the Tanganyika district of Africa, recent alluvial deposits and certain sandstones carry gold, platinum, and palladium, but so far only the placers are worked.

In North America platinum occurs in Columbia, associated with gold, chromite, titaniferous magnetite, and magnetite, while some of the sands also contain rhodium. Placers containing platinum and gold have been met with in the Sierra Nevada, and in California

in the Cherokee and Butte County districts. Many of the so-called 'black sands' of the United States have yielded good gold and platinum values in the concentrates.

In South America the most noted district is that of Minas Geraes, in Brazil.

THE RARE EARTHS.

Compounds containing the elements cerium, lanthanum, and didymium, with a certain proportion of thorium, yttrium, erbium, etc., are found primarily in many of the crystalline and metamorphic rocks, but in commercial quantities chiefly in placer deposits.

The mineral of chief economic importance is monazite, an anhydrous phosphate of cerium, lanthanum, and didymium, which usually contains some or all of the other elements mentioned above. The percentage of thoria, for instance, occasionally rises to 6·5, as in the monazite from Northern Carolina.

Monazite has been found and exploited in many widely separated regions. In the Bahia, Minas Geraes, Rio de Janeiro, and São Paulo districts of Brazil, it has been found in the porphyritic, granulitic, and schistose gneisses, and in granitic dykes. It occurs in the gneisses of Northern Carolina, in apatite-bearing rocks in Norway, and in pegmatites in Southern Norway, Silesia, Bohemia, etc.

It is a mineral conspicuously absent from the older sediments, but, like gold, it occurs in the recent placer deposits of rivers, in the irregular deposits of ancient streams, and in beach-placers.

The chief deposits which contain monazite occur in

North and South Carolina, in Brazil, at Sanarka in the Urals, in Liberia and Nigeria ; but deposits of economic importance are also known in the river-sands of Buenos Ayres in the Argentine, and in the gold-placers of Rio Chico (Venezuela), of Antioquia (Columbia), and of Siberia.

In the placers this mineral, which is usually associated with one or more of similar character, such as xenotime, fergusonite, jadolinite, samarskite, uraninite, etc., has undoubtedly been furnished by the crystalline rocks undergoing disintegration.   It has been concentrated naturally by reason of its high specific gravity (4·9 to 5·3) in the lower portions of the deposit, but those of the river placers nearest the head-waters are invariably the richer.

The monazite sands of Brazil, of which those of Prado are the most important, are derived from granites and gneisses.   They seldom exceed half a yard in thickness, and occasionally yield 70 per cent. of the mineral.

The North and South Carolina deposits were extremely rich, but are now largely exhausted.

In the year 1893-94 the United States alone yielded 676,855 pounds of monazite.

Iron and the Baser Metals.

Iron ores occur abundantly in certain beach-placers of the United States, New Zealand, and elsewhere, derived directly from basic igneous rocks, and generally known by the name of ' black sands.'   They result from a process of concentration carried on by the waves and tide between tidal limits.

In our own country, perhaps the best example is

the titaniferous iron sand of Porth Dinlleyn, in North Wales. Titaniferous iron oxide also occurs as a marine deposit on the seashores of Pahang.

The United States deposits are rich in magnetite, ilmenite, hæmatite, pyrite, chromite, and monazite, with apatite, zircon, garnet, epidote, etc. Magnetite and ilmenite are generally the most abundant heavy minerals.

In New Zealand, on the shores of the Tasman Sea near New Plymouth, occur titaniferous and magnetic iron-sands, which are derived directly from the horn-blende andesites and basic volcanic rocks of the district. Native copper and an alloy of the metals iron and nickel are not uncommon in some of the fluviatile and marine shallow placers. This iron-nickel alloy has already been mentioned in connection with the segregation of the native metals (p. 36).

Native copper occurs in some of the black sands mentioned above, and it has also been met with in the alluvium of the White River in Alaska.

The compounds of copper, and also those of iron other than the oxides, are distinctly rare in detrital deposits owing to the comparative ease with which they decompose under humid conditions. In Arizona, however, certain metasomatic copper veins have given rise to placers of some value, containing compounds of copper such as chalcopyrite and bornite in association with several other metallic sulphides and wolfram.

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